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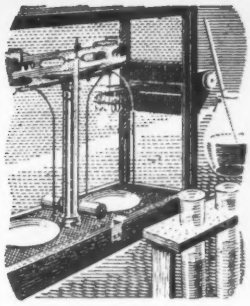

Atomic Interaction in Molten Alloy Steels

By John Chipman

SYNOPSIS

Interactions between two or more dissolved elements in liquid iron are examined through the effect of one on the activity coefficient of the other. Values of the parameter $\epsilon_i^j = \partial \ln f_i / \partial N_j$ in dilute solution show the effects of a number of dissolved elements on the activity coefficients of carbon, nitrogen, oxygen, silicon, and sulphur.

In concentrated solutions the effects are shown graphically. Recent data on the systems Fe–Cr–C and Fe–Cr–O are used to calculate the limiting carbon concentrations during oxidation of the stainless steel bath at temperatures of 1550–1850° C. 1105

Introduction

UP TO THE present time the research effort in the physical chemistry of steelmaking has been aimed almost entirely at understanding and controlling the processes used in making iron and carbon steel. Despite the enormous growth of alloy-steel production, little attention has been given in the laboratory to problems of alloy behaviour in the steel bath. The problems peculiar to alloy steelmaking, by and large, have been worked out in the melting shop; and so effective has this procedure been that one might question the necessity for laboratory studies in this highly developed field. It seems inevitable, however, that a more intimate knowledge of the effects of alloying elements upon reactions in the steel bath will lead to the same kind of progress in alloy steelmaking that we have witnessed in the making of iron and of carbon steels in the past few decades. With the rise of a younger generation of melters, the trend will be toward more detailed technical control based upon a more complete knowledge of alloy-steel bath chemistry.

One has only to look at the well-developed stainless steel industry to see the impact of one simple scientific truth: that more heat is evolved in the oxidation of chromium from the bath than from oxidation of an equivalent amount of carbon. It was the firm dependence upon this knowledge that enabled Alex Feild to develop the rustless process in which carbon is oxidized preferentially from chromium steel at a very high temperature. It led him to the solution of the crucial problem of remelting stainless scrap and removal of carbon from the resulting bath. The quantitative data on the chromium–carbon–temperature relation developed by Don Hilty currently serve as a valuable guide to the remelting and oxidation of chromium-bearing scrap and the elimination of carbon to meet phenomenally low specifications. The detailed understanding of the chromium–carbon interaction in the steel bath, resulting from the researches of Richardson and Dennis, is likely to point the way toward the next advance in the production metallurgy of iron–chromium alloys.

Today we face the possibilities for further development of a scientific understanding, which we may call the physical chemistry of alloy steelmaking. The problems to be studied are, for the most part, those resulting from the addition of alloying elements to the bath and their effects upon the familiar reactions of carbon steelmaking. Our present knowledge of the physical chemistry of ordinary steelmaking forms a necessary, but not yet completed, base upon which to build this understanding.

Since many of the reactions of steelmaking are rapid, the extent to which they occur under practical conditions is in large measure dependent upon the rate of supply of reactants and the laws of chemical equilibrium. It is with the latter factor that this paper is concerned, in particular with the effects of alloying elements upon those equilibria which have already received much attention under conditions analogous to those of carbon steelmaking.

Chemical equilibrium is governed by the law of mass action according to which we may determine an equilibrium constant for a reaction at a given temperature. For example, in the reaction

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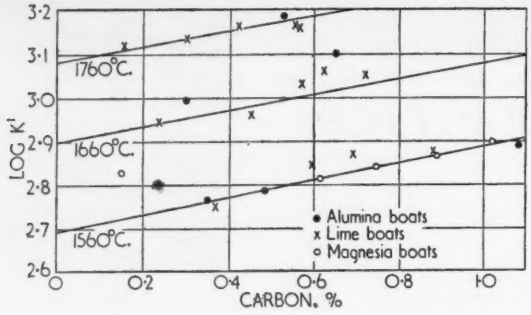

Fig. 1—Equilibrium of gases with carbon in liquid iron; $K' = p^2_{CO}/(p_{CO_2} \times \%C)$. Data of Richardson and Dennis[25]

$$A + B = AB$$

the equilibrium constant is

$$K = \frac{a_{AB}}{a_A \times a_B} = \frac{f_{AB} \times C_{AB}}{f_A C_A \times f_B C_B}$$

The C terms are concentrations expressed in any convenient unit, for example, weight-percentages. The a terms are activities; the f terms are activity coefficients usually measured on such a scale that they become equal to unity in the infinitely dilute solution. The thermodynamic properties of a solution may be expressed in terms of the activity coefficients and concentrations of its components.

Multicomponent Systems

The alloy steel bath is a multicomponent system, and it is to be expected that such a bath would be subject to manifold interactions between its components. It is fortunate that a simple mathematical treatment, which is correct for the infinitely dilute solution, forms a satisfactory basis for calculations concerning more highly alloyed baths.

When a solvent metal, 1, contains a number of solute metals, 2, 3, 4, etc., the activity coefficient of one of these, for example, f_2, may be expressed as a product of factors which represent the effects of each of the other components; thus in a solution of mole fractions x_2, x_3, x_4, etc.,

$$f_2 = f_2' \times f_2^{(3)} \times f_2^{(4)}$$

Here f_2' is the activity coefficient of 2 in the binary solution of mole fraction x_2. The following equivalent expression has been derived by Wagner[1]:

$$\ln f_2\,(x_2, x_3, x_4, \ldots) = \ln f_2^\circ + x_2 \frac{\partial \ln f_2}{\partial x_2} + x_3 \frac{\partial \ln f_2}{\partial x_3} + x_4 \frac{\partial \ln f_2}{\partial x_4} + \ldots$$

where the derivatives are to be taken for the limiting case of zero concentrations of all solutes, and higher order terms of a Taylor series are neglected. The term $\ln f_2^\circ$ is made zero by taking $f_2 = 1$ at infinite dilution. The derivatives are represented by the symbols $\varepsilon_2^{(3)}$, etc., defined as:

$$\varepsilon_2^{(2)} = \frac{\partial \ln f_2}{\partial x_2};\ \varepsilon_2^{(3)} = \frac{\partial \ln f_2}{\partial x_3};\ \text{etc.}$$

and the equation becomes:

$$\ln f_2\,(x_2, x_3, x_4, \ldots) = x_2 \varepsilon_2^{(2)} + x_3 \varepsilon_2^{(3)} + x_4 \varepsilon_2^{(4)} + \ldots \quad (1)$$

For convenience, common logarithms are used, and concentrations are expressed in weight-percentages; then

$$\log f_2\,(\%2, \%3, \%4, \ldots) = e_2^{(2)} \%2 + e_2^{(3)} \%3 + e_2^{(4)} \%4 + \ldots\ldots (1a)$$

$$= \log f_2' + \log f_2^{(3)} + \log f_2^{(4)} + \ldots$$

where

$$e_2^{(3)} = \frac{\partial \log f_2}{\partial\ \%3},\ \text{etc.}$$

Wagner has also shown that a simple relation exists between the effect of component i on f_j and the effect of component j on f_i:

$$\varepsilon_i^{(j)} = \varepsilon_j^{(i)} \quad (2)$$

The relations between e and ε for two elements of atomic weights M_i and M_j in the solvent metal, iron, are:

$$e_i^{(j)} = \frac{0{\cdot}2425}{M_j} \varepsilon_i^{(j)} = \frac{M_i}{M_j} e_j^{(i)} \quad (3)$$

THE CARBON–OXYGEN REACTION

The familiar reaction of the carbon boil comes to equilibrium when

$$K = \frac{p_{CO}}{[f_C\ \%C][f_O\ \%O]}$$

In this case the pressure of carbon monoxide is substituted for its activity. The f's are numbers which approach unity in the very dilute solution. In early applications of physical chemistry to steelmaking the f's were ignored, and it was considered that at constant pressure of CO the product %C. %O was constant and equal to about 0·0025 at 1600° C. It must be recognized that each alloying element may exert its own characteristic effect upon the activity of carbon and of oxygen, thus altering the equilibrium value of the product. This phenomenon is to be studied in terms of the effects of the alloying elements upon the activity coefficients of carbon and oxygen. But before discussing these and related studies, it is necessary to examine the data for the individual solutes, carbon and oxygen, and for their mutual effects on one another.

Carbon

The activity coefficient of carbon in liquid iron was studied by Richardson and Dennis[2] by means of the reaction*:

$$\underline{C} + CO_2(g) = 2CO(g);\ K = \frac{p^2_{CO}}{p_{CO_2}[f_C \times \%C]} \quad \ldots(4)$$

The simplest way to evaluate f_C from their data is by means of the plot shown in Fig. 1 wherein $\log K'$ is plotted against carbon concentration and K' is defined as $p^2_{CO}/p_{CO_2}[\%C]$. The data for 1560° C. define a straight line whose extrapolation to 0% C (where $f_C = 1$) yields the value of $\log K$. The value of $\log f_C$ at any concentration is given by the difference,

*The underlined symbol $\underline{C}$ denotes carbon dissolved in liquid iron, the concentration being expressed as weight-percentage.

$\log K' - \log K$, which at 1560° C. is

$$\log f_C = +0{\cdot}195[\%C] \quad \ldots\ldots(5)$$

At the other experimental temperatures the data do not define so precisely a straight line. They are fairly well fitted, however, by straight lines whose slopes are estimated to be inversely proportional to absolute temperature in accordance with considerations discussed by Darken and Gurry.[3] For the range of temperature and concentration studied by Richardson and Dennis, the activity coefficient of carbon is given by the equation:

$$\log f_C = \frac{358}{T}[\%C] \quad \ldots\ldots(5a)$$

Oxygen

The activity coefficient of oxygen in binary Fe–O solutions has been found to be independent of concentration. This conclusion is reached from the observed constancy of the equilibrium ratio p_{H_2O}/p_{H_2} [%O] in the experiments of Fontana and Chipman.[4] Accordingly, in the binary system f_O is unity at all concentrations. In multicomponent systems, however, the activity coefficient is no longer unity, and it becomes important to determine the effect of each added element on the value of f_O.

The Carbon–Oxygen Reaction

The product [%C][%O] in equilibrium with carbon monoxide at 1 atm. is not constant but rises gradually with increasing carbon content. The data of Marshall and Chipman[5] at 1540° C. are alone in extending observations of this reaction to high carbon content. There is fairly good agreement[6, 7] that at low carbon levels the product has a value of 0·0020–0·0025 at steelmaking temperatures. There is no agreement at all regarding the effect of higher carbon contents on this product,[8] and since only the one set of experimental data at high carbon concentrations is available, the following treatment will be based entirely upon it.

Marshall and Chipman expressed their results as values of $K' = p_{CO}/[\%C][\%O]$ for carbon concentrations up to 2·3% and CO pressures up to 20 atm. While the results showed an undesirably large scatter, there was a clear indication that K' decreases with increasing carbon. The data are reviewed in " Basic Open Hearth Steelmaking "[9] where average results are given which may be represented by the equation:

$$\log K' = 2{\cdot}67 - 0{\cdot}22\,[\%C] \quad \ldots\ldots(6)$$

The extrapolated value of K' at zero carbon represents the constant $K = p_{CO}/[f_O\ \%C][f_C\ \%O]$. These relations lead to evaluation of the product $f_C f_O$ or, more simply, the sum of their logarithms:

$$\log f_C + \log f_O = \log K' - \log K = -0{\cdot}22\,[\%C]$$

When each of the activity coefficients is factored, we have:

$$\log f'_C + \log f_C^{(O)} + \log f'_O + \log f_O^{(C)} = -0{\cdot}22\,[\%C]$$

It has been shown that $\log f'_O = 0$, and it may be assumed that $\log f_C^{(O)}$ is negligible in all but the lowest carbon concentrations. With this simplification, the above result can be combined with equation (5) to yield an interaction term for the effect of carbon on activity of oxygen, namely:

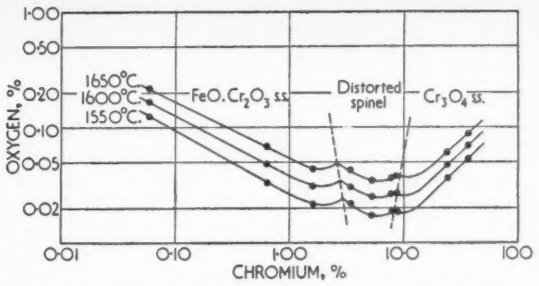

Fig. 2—Solubility of oxygen in iron–chromium alloys. Data of Hilty, Forgeng, and Folkman[11]

$$\log f_O^{(C)} = -0{\cdot}41\,[\%C] \quad \ldots\ldots(7)$$

The reciprocal term for the effect of oxygen on activity of carbon (from equation (3)) is:

$$\log f_C^{(O)} = -\frac{12}{16} \times 0{\cdot}41\,[\%O] = -0{\cdot}31\,[\%O] \ldots(8)$$

These results must be considered only rough approximations since they can be no better than the data on which they are based. It must be remembered that at the present time we have no accurate information on the equilibrium oxygen content at very high carbon concentrations.

EFFECTS OF ALLOYING ELEMENTS ON OXYGEN

Chromium

The first study of the activity of oxygen in an alloyed bath was that of Chen and Chipman[10] using the reaction

$$H_2(g) + \underline{O} = H_2O(g)$$

They found that, for a given ratio p_{H_2O}/p_{H_2} (low enough to avoid formation of an oxide phase), the equilibrium oxygen concentration of the bath was doubled when the chromium content was raised from zero to about 7%. This is equivalent to the statement that addition of 7% Cr reduces the activity coefficient of oxygen to 0·5. Their results in the range 0–10% Cr may be summarized by the very simple statement that $e_O^{(Cr)} = -0{\cdot}041$ throughout this range.

At higher chromium levels additional information may be deduced from measurements of the solubility of oxygen in iron–chromium alloys reported by Hilty, Forgeng, and Folkman,[11] to whom the author is indebted for a copy of their paper in advance of publication. These investigators have shown that the oxide phases in equilibrium with iron–chromium–oxygen melts at 1600° C. are the following: (i) between 0·06 and 3% Cr, chromite; (ii) between 3 and 9% Cr, distorted spinel; (iii) above 9% Cr, Cr_3O_4 solid solution containing some iron oxide. Presumably all three of these phases are of variable composition capable of being represented by the formula $Fe_xCr_{3-x}O_4$, although the ratio of metal to oxygen may deviate from 3 : 4. Apparently certain ranges of stability exist, the limits of which have not been established. As a very rough approximation, it would appear that in chromite $x \geqslant 1{\cdot}0$; in the distorted spinel $x < 1{\cdot}0$; and in 'Cr_3O_4 s.s.' $x < 0{\cdot}3$. Data on the compositions of liquid alloys in equilibrium with these solid phases,

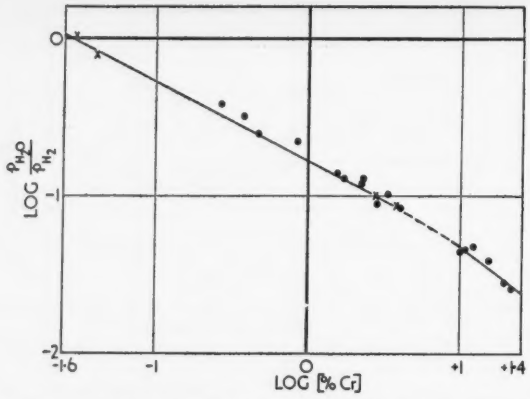

Fig. 3—Equilibrium in the reaction of water vapour with chromium in liquid iron at 1595° C. Data of Chen and Chipman[10]

as reported by Hilty and co-workers, are shown in Fig. 2.

The work of Chen and Chipman must be re-examined in the light of this new information. Their three-phase equilibria—metal, oxide, gas—may be represented by the following:

$$Fe_xCr_{3-x}O_4 + 4H_2 = xFe + (3 - x)\underline{Cr} + 4H_2O$$

The solution of Cr in Fe has been shown to be approximately ideal,[10] and since the atomic weights are not far apart, we may take the activities as proportional to weight-fractions. For convenience the activity of Cr is taken equal to its weight-percentage whilst that of Fe is its weight-fraction, indicated by C_{Fe}. The equilibrium constant then becomes:

$$K = [C_{Fe}]^x \cdot [\%Cr]^{3-x}\left(\frac{p_{H_2O}}{p_{H_2}}\right)^4$$

A plot of log (p_{H_2O}/p_{H_2}) against log chromium concentration should yield a straight line whose slope is $(3 - x)/4$, provided that x log $[C_{Fe}]$ is negligible. Such a plot is shown in Fig. 3, which includes the equilibrium data in the first and third ranges, 0–3% and 9–21% Cr. Occasion is taken to correct the plotting of Chen's runs 205 and 206, reversed in the original publication, and to note a misplaced decimal in the tabulated chromium content of runs 203 and 204, which were correctly plotted in the original. Lines are drawn with slopes of $\frac{1}{2}$ and $\frac{3}{4}$. In the first range $[C_{Fe}]$ is essentially one, and in the third range x is very small; the slopes correspond to solid phases of composition $FeCr_2O_4$ and Cr_3O_4. In the chromite range the selected slope fits the data quite well, but in the Cr_3O_4 range the data would be better served by a line of steeper slope, e.g. one corresponding to CrO. Substitution of a slope corresponding to $x = 0{\cdot}3$ worsens the fit, and hence the line as drawn will be used for purposes of extrapolation. Data in the second range are too scattered to define a line; the broken line merely connects points on the other two corresponding to 3 and 9% of chromium. Lack of constancy in the composition of the solid phase would lead to curvature of the equilibrium line. To establish such a curvature would require an experimental precision which has not been attained in high-temperature research.

Taking the composition of the solid phases as $FeCr_2O_4$ and Cr_3O_4, the data give the following for the experimental temperature, 1595° C.:

$$\log [C_{Fe}][\%Cr]^2\left(\frac{p_{H_2O}}{p_{H_2}}\right)^4 = -3{\cdot}09$$

$$\log [\%Cr]^3\left(\frac{p_{H_2O}}{p_{H_2}}\right)^4 = -2{\cdot}27$$

and the corresponding values of ΔG°_{1868} are + 26,400 and + 19,400 cal., respectively.

Free Energy of Chromium Oxide Phases

The heat of formation of Cr_2O_3 is given by Brewer[12] as $\Delta H = -270 \pm 1$ kcal., whilst more recent work by Mah[13] gives $-272{\cdot}7 \pm 0{\cdot}4$ kcal. With the aid of Kelley's tables[14] of entropy and enthalpy, the latter value becomes $-270{\cdot}5$ kcal. at 1800° K., and the entropy change at that temperature is $-60{\cdot}9$ e.u. For the union of FeO and Cr_2O_3 to form chromite, Richardson and Jeffes[15] find $\Delta H = -12{\cdot}2$ kcal. and $\Delta S = -1{\cdot}8$ e.u. at temperatures above the melting point of wüstite. From these data the following equation, applicable between the melting points of wüstite and chromium, is derived:

$$FeO(l) + 2Cr(s) + \tfrac{3}{2}O_2(g) = FeCr_2O_4(s) \quad \ldots\ldots(9a)$$

$$\Delta G^\circ = -282{,}700 + 62{\cdot}7T \text{ (tentative)}$$

The heat of formation of Cr_3O_4 may be roughly estimated as four-thirds that of Cr_2O_3. The value of ΔS is probably about the same as that of Mn_3O_4, which is known. Assuming further that the effect of temperature is the same as in the case of Mn_3O_4, given by Kelley, the following approximate equation results:

$$3Cr(s) + 2O_2(g) = Cr_3O_4(s) \quad \ldots\ldots(10a)$$

$$\Delta G = -349{,}000 + 74T \text{ (tentative)}$$

The method of estimation gives more confidence in the entropy than in the heat term, and the latter will be adjusted to conform to the equilibrium data.

The following free energy equations are quoted from "Basic Open Hearth Steelmaking."[9] The first is based on data of the Bureau of Standards Selected Values,[16] the second on equilibrium studies, and the third on ideality of the Fe–Cr liquid solution.

$$H_2(g) + \tfrac{1}{2}O_2(g) = H_2O(g);\ \Delta G^\circ = -60{,}180 + 13{\cdot}93T \quad \ldots\ldots(11)$$

$$H_2(g) + \underline{O} = H_2O(g);\ \Delta G^\circ = -32{,}250 + 14{\cdot}50T \quad (12)$$

$$Cr(s) = \underline{Cr};\ \Delta G^\circ = +4350 - 11{\cdot}11T \quad \ldots\ldots(13)$$

Proper combination among equations (9)–(13) yields the following, which are tentative only:

$$FeCr_2O_4 + 4H_2 = Fe(l) + 2\underline{Cr} + 4H_2O \quad \ldots\ldots(14a)$$

$$\Delta G^\circ = +102{,}100 - 41{\cdot}1T \text{ (tentative)}$$

$$Cr_3O_4 + 4H_2 = 3\underline{Cr} + 4H_2O \quad \ldots\ldots(15a)$$

$$\Delta G^\circ = +121{,}300 - 51{\cdot}6T \text{ (tentative)}$$

The experimentally determined values for ΔG° at 1868° K. are now used to adjust these equations, assuming that the entropy terms are correct and altering the heat terms to fit the equilibrium data, thus:

$$\Delta G^\circ = +103{,}200 - 41{\cdot}1T \ldots\ldots\text{(adjusted) (14)}$$

$$\Delta G^\circ = +115{,}800 - 51{\cdot}6T \ldots\ldots\text{(adjusted) (15)}$$

The tentative equations for free energy of formation of the oxides are revised accordingly, yielding heats of formation which are well within the limits of accuracy of existing data:

$$FeO(l) + 2Cr(s) + \tfrac{3}{2}O_2(g) = FeCr_2O_4(s) \quad \ldots\ldots(9)$$
$$\Delta G^\circ = -283{,}800 + 62{\cdot}7T \text{ (adjusted)}$$
$$3Cr(s) + 2O_2(g) = Cr_3O_4(s) \quad \ldots\ldots(10)$$
$$\Delta G^\circ = -344{,}500 + 74{\cdot}0T \text{ (adjusted)}$$

The chromium–oxygen relation along the line of saturation may be calculated by combining equation (12) with equation (14) or (15) to yield the following:

$$FeCr_2O_4(s) = Fe(l) + 2\underline{Cr} + 4\underline{O} \quad \ldots\ldots(16)$$
$$\Delta G^\circ = +232{,}200 - 99{\cdot}1T$$
$$Cr_3O_4(s) = 3\underline{Cr} + 4\underline{O} \quad \ldots\ldots(17)$$
$$\Delta G^\circ = +244{,}800 - 109{\cdot}6T$$

It is convenient to divide the foregoing equations by 4, taking the one-fourth power of the indicated equilibrium constant. The activity of Fe within the chromite range is taken as unity, that of chromium throughout as its weight-percentage; then

$$\log [\%Cr]^{\frac{1}{3}}[f_O \times \%O] = -12{,}690\ T + 5{\cdot}41 \quad (0\text{–}3\%Cr) \quad \ldots\ldots(16')$$
$$\log [\%Cr]^{\frac{1}{3}}[f_O \times \%O] = -13{,}380\ T + 5{\cdot}99 \quad (\text{above } 9\%\ Cr) \quad \ldots\ldots(17')$$

Solution of these equations at several chromium concentrations yields values of the term $[f_O\ \%O]$ which are then combined with Hilty's observed solubilities, expressed as %O, to give values of the activity coefficient f_O. Values so obtained at 9, 24·7, and 37% Cr are shown in Fig. 4 along with the old data of Chen and Chipman at 0–10% Cr and the recent results of Turkdogan[17] up to 12% Cr. It is evident that the three sets of data are in very good agreement. At low concentrations $e_O^{(Cr)} = -0{\cdot}041$, but the line becomes curved above about 10% Cr. Results at two other temperatures are shown by broken lines at high chromium concentrations only. The effect of temperature appears to be greater than if $e_O^{(Cr)}$ were inversely proportional to absolute temperature.

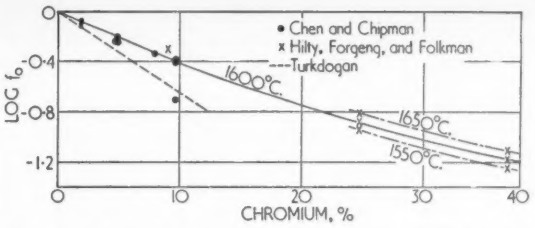

Fig. 4—Effect of chromium on activity coefficient of oxygen in liquid iron

Other Alloying Elements

The effects of a number of other alloying elements have been studied but only at relatively low concentrations. Using again the steam/hydrogen ratio to fix the activity of oxygen, Dastur[18] found at 1600° C. that $e_O^{(V)} = -0{\cdot}27$. Chipman and Gokcen[19] concluded that the effect of silicon on oxygen activity was enough to approximately offset the increase in activity coefficient of silicon itself with increasing concentration, so that the equilibrium product $[\%Si][\%O]^2$ remained approximately constant. This would mean, very roughly, that $e_O^{(Si)} = -0{\cdot}02$.

The effect of aluminium appears to be much larger, but in view of the extreme experimental difficulties encountered at very low concentrations of aluminium and oxygen, the results of Gokcen and Chipman[20] indicate only that as a rough approximation at 1600° C., $e_O^{(Al)} = -12$.

Similar experiments carried out by Jacques Thiery in the writer's laboratory indicate that the activity coefficient of oxygen is not appreciably affected by the presence of several per cent. of manganese. This is in agreement with the observation that the ratio of (FeO) in simple slags to [O] in liquid metal is not altered by the presence of manganese.

Recent experiments by H. A. Wriedt[21] have shown that nickel has a very slight effect on oxygen activity. A gas of controlled H_2O/H_2 ratio which is in equilibrium with 0·10% of oxygen in liquid iron is found to equilibrate with 0·075% of oxygen in a 25% Ni alloy. The value of f_O in this alloy is thus 1·33 and $e_O^{(Ni)} = +0{\cdot}005$.

The experiments of Bookey, Richardson, and Welch[22] on the equilibrium

$$2\underline{P} + 5H_2O(g) + 4CaO(s) = Ca_4P_2O_9(s) + 5H_2(g)$$

showed that phosphorus diminishes the activity coefficient of oxygen. The amount of this decrease can be estimated from their data for 1560° and 1580° without attempting to explain the slope of their observed line for 1540° C. Their points 12 and 17, at high oxygen concentration, agree roughly in evaluating $\Delta \log [\%P]/a_O = +1{\cdot}7$, where $\Delta \log [\%P]$ represents the deviation from the theoretical line. The activity of oxygen is lowered by the presence of phosphorus, and one might estimate that the above corresponds to Δ log $[\%P]/[\%O] = +1{\cdot}5$. From this we have $d \log f_P/d\,[\%O] = -1{\cdot}5$, and by equation (3), $e_O^{(P)} = -0{\cdot}8$. This is but a very rough estimate.

Hilty and Crafts[23] reported that the solubility of oxygen in liquid iron is substantially diminished by addition of 0·1% S. Dilution of the oxide slag by sulphide is not sufficient to account for their results, which must be regarded as indicative of an increase in activity coefficient of oxygen. Their results lead to an approximate value of $e_O^{(S)} = +1{\cdot}0$.

Dastur and Chipman[24] found that the oxygen concentration in liquid iron in equilibrium with a gas of given ratio p_{H_2O}/p_{H_2} is independent of dilution with an inert gas, provided that thermal separation is absent. Since the hydrogen content of the metal undoubtedly varied during these experiments, it may be concluded that hydrogen has no very large effect on f_O. The highest hydrogen pressure was of the order of 1 atm., and the result does not preclude possible effects at concentrations corresponding to higher pressures.

The foregoing discussion of the effects of alloying elements on the activity of oxygen are summarized below. It should be emphasized that these effects

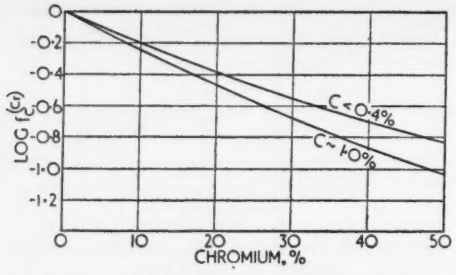

Fig. 5—Effect of chromium on activity coefficient of carbon. Data of Richardson and Dennis[25]

constitute only one phase of the problem of deoxidation. Attention has been focused here on properties of the homogeneous liquid metal phase which are independent of the presence of a deoxidation product or other solid phase.

Added Element, j	$e_O^j = \log f_O^{(j)}$ at 1% j
C	−0·41
Mn	0
Cr	−0·041
V	−0·27
Si	−0·02
Al	−12
P	−0·8
S	+1·0
Ni	+0·005

EFFECTS OF ALLOYING ELEMENTS ON CARBON

Chromium

Richardson and Dennis[25] determined the condition of equilibrium in the reaction of CO/CO_2 mixtures with carbon in liquid iron–chromium–carbon alloys, and their data lead to an evaluation of the effect of chromium on the activity coefficient of carbon. The author is indebted to Mr. André Rist for the treatment which follows and for that used in an earlier section on the binary Fe–C solutions.

The activity coefficient of carbon is expressed thus:

$$\log f_C = \log f'_C + \log f_C^{(Cr)}$$

Values of $\log f'_C$ have been deduced from the binary Fe–C solution and are given in equation (5). Values of $\log f_C^{(Cr)}$ are shown in Fig. 5. The data at 9–10% Cr are very consistent and yield values of $f_C^{(Cr)}$, which are nearly independent of carbon concentration and temperature, and which are fairly well represented by $e_C^{(Cr)} = -0{\cdot}020$. At higher chromium concentrations, however, $f_C^{(Cr)}$ is dependent upon carbon concentration as well as temperature, and the former seems to have the greater effect. The data are represented as a band, the upper edge of which applies to the lowest carbon concentrations and the lower edge to approximately 1% C. Increasing temperature favours the upper edge of the band.

Decarburization of Chromium Steels

In the decarburization of chromium steels by oxidation with slag or gaseous oxygen, the formation of a solid oxide phase establishes an upper limit to the oxygen content of the bath. Since the decarburization reaction depends upon evolution of carbon oxides against atmospheric pressure, a lower limit is thus set for carbon content. This limit was calculated by Dennis and Richardson[26] for high-chromium steels in the presence of Cr_2O_3. The following is a revision of this calculation for the solid phases reported by Hilty, Forgeng, and Folkman.[11]

The carbon content of metal in equilibrium with the solid oxide phases and with $CO + CO_2$ at 1 atm. total pressure can be calculated from the free energy of the oxides, equations (16) and (17), together with the activity coefficient of carbon, equation (5*a*) and Fig. 5, with the further aid of the free energy of formation of the two gases from the dissolved elements. The latter are quoted from "Basic Open Hearth Steelmaking":

$$\underline{C} + \underline{O} = CO(g);\ \Delta G^\circ = -8510 - 7{\cdot}52T \ldots\ldots(18)$$

$$\underline{C} + 2\underline{O} = CO_2(g);\ \Delta G^\circ = -46{,}560 + 13{\cdot}20T \ldots(19)$$

$$CO(g) + \underline{O} = CO_2(g);\ \Delta G^\circ = -38{,}050 + 20{\cdot}72T(20)$$

For equilibrium with chromite, equations (16) and (18) give:

$$FeCr_2O_4 + 4\underline{C} = Fe(l) + 2\underline{Cr} + 4CO(g)\ldots\ldots(21)$$

$$\Delta G^\circ = +198{,}200 - 129{\cdot}2T$$

The equilibrium constant is conveniently written for one mole of CO and $\frac{1}{2}$ atom of Cr, for which,

$$\log([\%Cr]^{\frac{1}{2}} p_{CO}/a_C) = -10{,}830\ T + 7{\cdot}06 \ldots(21a)$$

Similarly for equilibrium with Cr_3O_4, equations (17) and (18) give:

$$Cr_3O_4 + 4\underline{C} = 3\underline{Cr} + 4CO(g)\ldots\ldots\ldots\ldots(22)$$

$$\Delta G^\circ = +210{,}760 - 139{\cdot}68T$$

and

$$\log([\%Cr]^{\frac{3}{2}}\ p_{CO}/a_C) = -11{,}520\ T + 7{\cdot}64\ldots\ldots(22a)$$

In the composition range of chromite stability, the carbon concentration is low, and the equilibrium gas contains an appreciable fraction of CO_2. Its ratio to that of CO is readily calculated by means of the foregoing equations, and hence the pressure of CO corresponding to 1 atm. total pressure is obtained. In the higher chromium range the pressure of CO_2 does not exceed about 0·01 atm. and that of CO may therefore be taken as unity.

The equations may be solved for the activity of carbon corresponding to 1 atm. total pressure and

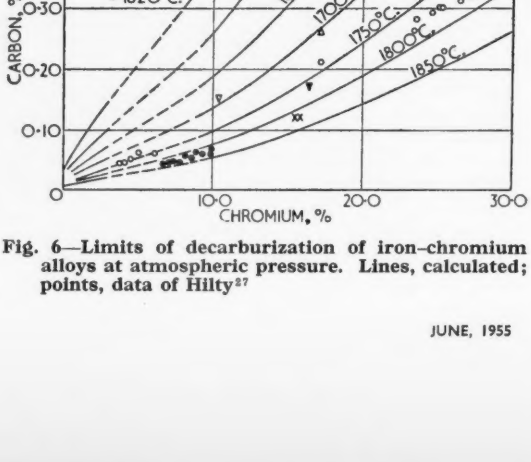

Fig. 6—Limits of decarburization of iron–chromium alloys at atmospheric pressure. Lines, calculated; points, data of Hilty[27]

various concentrations of chromium. Then with the aid of the activity coefficients of equation (5) and using the upper edge of the band in Fig. 5, the equilibrium carbon concentrations may be obtained. The results of these computations are shown in Fig. 6. The broken lines between 3 and 9% Cr, where the stable solid phase is the distorted spinel, were drawn to connect these points and involved no calculations. Hilty's[27] experimental data are shown for comparison. At low chromium concentrations the agreement is excellent. Above 20% Cr a slight divergence is noted which may be attributed to uncertainties in the extrapolation of Chen's data or in the activity coefficient of carbon at high chromium concentrations, or to the precarious assumption that the experiments correspond to an equilibrium pressure of 1 atm.

Other Elements

The effect of molybdenum was studied in the author's laboratory by H. Manley using methods similar to those of Richardson and Dennis. He found that 10% Mo lowered the activity coefficient of carbon about 5%, from which $e_C^{(Mo)} = -0{\cdot}002$.

The effect of other elements on the activity coefficient of carbon can be obtained for those cases where the effect of the third element on the solubility of graphite has been measured. In graphite-saturated solution the activity of carbon is constant, from which it follows that:

$$\partial \log f_C / \partial N_j = -\partial \log N_C / \partial N_j \text{ (in the saturated solution)}$$

The result applies to a saturated solution rather than to infinite dilution, and therefore does not, in general yield a direct value for $\varepsilon_C^{(j)}$. In some cases, however, an approximate value may be obtained.

Data[28] on the Fe–Mn–C system show that the solubility of graphite is increased about 0·5% for each 0·01 increment in N_{Mn}. This means that, as an approximation, $\varepsilon_C^{(Mn)} = -0{\cdot}5$ and $e_C^{(Mn)} = -0{\cdot}002$.

Similar data[28, 29] on the Fe–Si–C system at 1600° C. show a gradually changing value of $\partial \log N_C / \partial N_{Si}$ from $-1{\cdot}62$ at low Si and high C to $-4{\cdot}4$ at the highest silicon concentrations studied, 23% Si. The latter value corresponds to a mole fraction of carbon of only 0·0155 and may be taken as representing

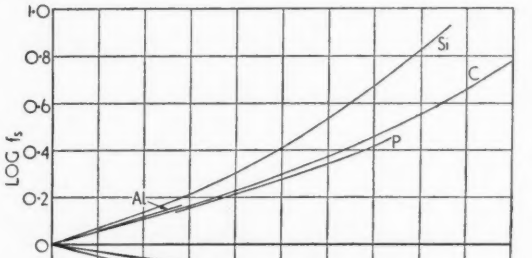

Fig. 7—Comparison of the effects of several elements on the activity coefficient of sulphur

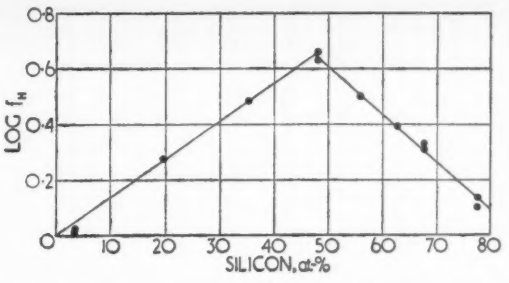

Fig. 8—Effect of silicon on the activity coefficient of hydrogen in iron. Data of Liang, Bever, and Floe[33]

$-\partial \log f_C / \partial N_{Si}$ at essentially 0% C. If the effect of silicon is assumed linear, $\varepsilon_C^{(Si)} = 2{\cdot}3 \times 4{\cdot}4 = +10{\cdot}1$, and $e_C^{(Si)} = +0{\cdot}088$. The effects of four elements on the activity coefficient of carbon are given below:

Added Element, j	$e_C^{(j)} = \log f_C^{(j)}$ at 1 % j
Cr	−0·020
Mn	−0·002
Si	+0·088
Mo	−0·002

EFFECTS OF ALLOYING ELEMENTS ON SULPHUR

Subsequent to the important investigations of Morris and co-workers,[30a, b] the effects of a number of addition agents on the reaction

$$H_2(g) + \underline{S} = H_2S(g)$$

have been studied. Since a review of these studies was included in the recent paper of Sherman and Chipman,[30c] it will be sufficient here to show their summarizing figure and to add a few data of more recent origin. Their summary is represented in Fig. 7.

A very recent investigation by Jean Cordier[31] in the author's laboratory has established the effect of nickel. Very briefly, it was found that in iron–nickel alloys the sulphur equilibrium is exactly the same, within limits of experimental error, as in iron. This surprising equality covers the entire range of compositions including pure nickel. It is expressed by the statement $e_S^{(Ni)} = 0$.

An interesting study of sulphur in quaternary solutions Fe, C, Mn, S was reported by Morris[32] who compared f_S in these solutions with its value in Fe, C, S solutions of the same C and S concentrations. His results show clearly that the effect of manganese is independent of carbon concentration, being essentially the same at carbon saturation as in the carbon-free solutions. They are summarized by $e_S^{(Mn)} = -0{\cdot}023$, which agrees very closely with the slope of the line in Fig. 7.

It should be pointed out that, whilst these studies have contributed to an understanding of desulphurization in blast-furnace and open hearth, they have only begun to touch upon problems of alloy steelmaking. Further information is needed on the effects of other alloying elements, especially those which form the more stable sulphides. The factors which have been determined are:

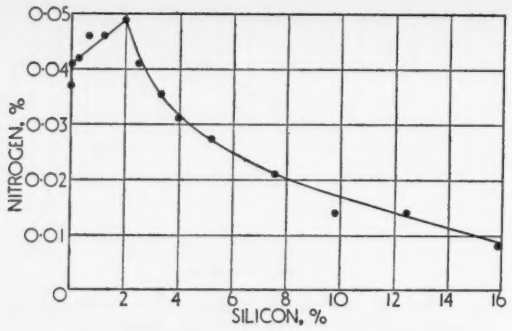

Fig. 9—Effect of silicon on solubility of nitrogen at 1630° C. Data of Vaughan and Chipman[36]

Added Element, j	$e_S^{(j)}$
C	+0·110
Si	+0·065
P	+0·042
Mn	−0·025
Al	+0·055
Cu	−0·012
Ni	0·000

EFFECT OF ALLOYING ELEMENTS ON HYDROGEN

The effect of an added element on the solubility of hydrogen or nitrogen at constant pressure provides a direct measure of its effect on the activity coefficient. If C_H is the solubility in the alloy and C_H° that in iron, in any convenient units, then

$$\log f_H = \log C_H^\circ - \log C_H$$

The solubility of hydrogen in molten iron–silicon alloys was measured by Liang, Bever, and Floe.[33] Their data at 1550° and 1650° C. are shown in Fig. 8. In the range 0–47 at.-% Si, $\varepsilon_H^{(Si)} = +3{\cdot}16$, or $e_H^{(Si)} = +0{\cdot}027$. Effects of other addition elements are unknown.

EFFECT OF ALLOYING ELEMENTS ON NITROGEN

The solubility data of Brick and Creevy[34] show a linear effect of Cr on $\log f_N$ up to about 14% Cr. The effect of vanadium was also determined but only in an approximate manner. The data are represented by $e_N^{(Cr)} = -0{\cdot}046$ and $e_N^{(V)} = -0{\cdot}09$.

Eklund[35] reported a marked decrease in solubility of nitrogen in the presence of carbon. His results in the range 0–4% C are represented by $e_N^{(C)} = +0{\cdot}13$.

The solubility of nitrogen in Fe–Si alloys was measured by Vaughan and Chipman[36] whose results at about 1630° C. are shown in Fig. 9. They found an increased nitrogen solubility up to about 2% Si followed by a decreased solubility and the formation of a heavy smoke at higher silicon. This latter phenomenon was accompanied by a slow apparent absorption of gas and was attributed to the formation, vaporization, and condensation of silicon nitride. The curve of decreasing nitrogen represents the solubility of the nitride in the melt. The line of Fig. 9 differs from that drawn by the original authors and is based upon the following treatment.

Above 2% Si a nitride of presumed composition Si_3N_4 forms and gradually volatilizes. Its presence

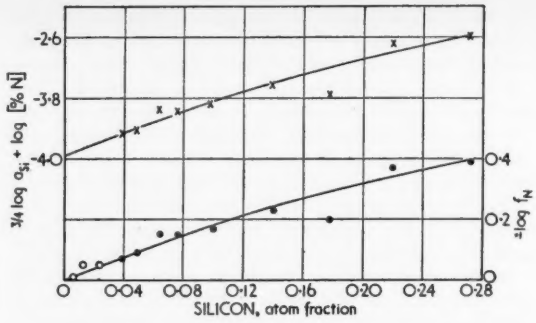

Fig. 10—Effect of silicon on solubility of Si_3N_4 and on activity coefficient of nitrogen

as a solid phase determines the equilibrium represented as:

$$\tfrac{1}{4}\,Si_3N_4(s) = \tfrac{3}{4}\,\underline{Si} + \underline{N};\quad K = [a_{Si}]^{\frac{3}{4}}[f_N \cdot \%N]$$

The activity of silicon in liquid iron–silicon alloys is now known,[29] and the concentration of nitrogen is too small to affect the values determined for the binary system. Accordingly, all terms of the equilibrium constant are known except f_N which is determined as follows.

Figure 10 contains values of $\frac{3}{4}\log a_{Si} + \log [\%N]$ plotted (upper line) against atomic fraction of silicon. Extrapolation to zero Si (where $f_N = 1$) gives $\log K = -3{\cdot}96$. A value of $\log f_N$ is obtained by subtracting the ordinate plotted in the diagram from $-3{\cdot}96$, and the results are shown in the lower curve. Values of $\log f_N$ for three points below 2% Si, calculated in the usual way, are also shown. The slope of the line at low concentrations gives $\log f_N = -1{\cdot}9\,N_{Si}$, or by equation (3), $e_N^{(Si)} = -0{\cdot}038$.

If the nitride which forms is actually Si_3N_4, the data determine its free energy at approximately 1900° K. For the reaction $Si_3N_4 = 3Si(l) + 4\underline{N}$, $\Delta G^\circ = -4RT\ \ln K = +137{\cdot}7$ kcal. For the solution of 2 moles of N_2 in Fe, $\Delta G^\circ = -4RT\ \ln 0{\cdot}041 = +48{\cdot}1$ kcal. Therefore, for $3Si(l) + 4N_2(g) = Si_3N_4(s)$, $\Delta G^\circ = -89{\cdot}6$ kcal. This would represent a higher order of stability than the nitride studied by Hincke and Brantley,[37] and the solid may, therefore, be another nitride. If it is SiN, the data for $f_N^{(Si)}$ will require only a slight revision.

The effects of added elements on nitrogen are summarized below:

Added Element, j	$e_N^{(j)} = \log f_N^{(j)}$ at 1% j
C	+0·13
Si	−0·038
Cr	−0·046
V	−0·09

EFFECTS OF ALLOYING ELEMENTS ON SILICON

The effects of several elements on the activity of silicon have been calculated[38] from Korber's[39] equilibrium data for the reaction:

$$SiO_2(s) + 2\underline{Mn} = \underline{Si} + 2MnO \text{ (in saturated slag)}$$

Since the activity of Mn was found to be independent

Table I

ATOMIC INTERACTIONS IN LIQUID IRON

Values of the Parameter $\epsilon_i^{(j)} = \partial \ln f_i / \partial N_j$

i	Added Element j										
	C	Al	Si	P	S	V	Cr	Mn	Ni	Cu	Mo
H			+ 3·16								
C	+ 9·8		+10				−4·3	−0·5			−0·8
N	+ 7·0		− 4·5			−19	−9·9				
O	−21 ?	−1300 ?	− 2 ?	−100 ?	+130	−57	−8·8	0·0	+1·2		
Si	+10		+ 3·4	+ 11				0·0	+1·2		
S	+ 6·0	+ 6·5	+ 7·6	+ 5·7	− 3·8			−5·7	0·0	−3·2	

of the concentration of Si in the alloy studied,[39b] and the activities of SiO_2 and MnO are fixed, the effects of added elements on silicon concentration are ascribed to their effects on its activity coefficient. Addition of C, P, or Ni lowered the equilibrium concentration of Si and increased the value of f_{Si}. Recalculation[29] of the effect of carbon, taking into consideration the small effect of C on f_{Mn}, led to a value of $\log f_{Si}^{(C)} = + 4{\cdot}4\ N_C$, which corresponds to $\varepsilon_{Si}^{(C)} = + 10$, or $e_{Si}^{(C)} = 0{\cdot}20$. This result is more nearly applicable to low concentrations at 1600° than is the slightly higher result reported[29] for higher concentrations and at 1420° C.

Added Element, j	$e_{Si}^{(j)} = \log f_{Si}^{(j)}$ at 1 % j
C	+0·20
P	+0·085
Mn	0·0
Ni	+0·005

DISCUSSION

The experimental data are summarized in Table I in which are listed values of the parameter $\varepsilon_i^{(j)} = \partial \ln f_i / \partial N_j$ at temperatures approximating to 1600° C. In obtaining $\varepsilon_i^{(j)}$ from the corresponding experimental value of $e_i^{(j)}$, it should be noted that the relation expressed in equation (3) is strictly valid only at infinite dilution. Values of $\varepsilon_i^{(j)}$ obtained from an experimental plot of $\log f_i$ against N_j over a wide concentration range may differ slightly from that obtained from the same data plotted against weight-percentages. The difference is significant only for elements whose atomic weight is considerably different from that of iron, and in Table I the parameters for added elements of atomic weight less than 30 have been obtained from plots of $\log f_i$ against N_j. Certain of the entries are indicated as questionable for reasons mentioned in the text. The others are based upon apparently reliable experimental results in which, however, the degree of precision is somewhat variable. In only one case, that of carbon and silicon, can equation (2) be tested, and in this instance the agreement is excellent.

In terms of interatomic attraction the negative values may be understood on the basis of a very simple model, illustrated by the Fe–Cr–O solutions. In Fe–O solutions each O atom is surrounded on the average by n Fe atoms which share the Fe–O bonding energy. The Cr–O bonding is stronger than the Fe–O bonding, and this leads to two results: the ratio Cr/Fe is greater amongst the nearest neighbours of O than in the bulk of the solution, and the O atoms become more firmly bonded as the Cr concentration increases.

The effect of V on O is greater than that of Cr, while that of Mn is less, and in the case of Ni the oxygen bonding is weaker than in iron. The abnormally large negative value of $\varepsilon_O^{(Al)}$ is subject to great experimental uncertainty but is indicative of a large Al–O bonding energy. In this case the simple model is modified by a substantial Al–Fe bonding energy, resulting in the surrounding of Al atoms by Fe. The large negative ε indicates strong attraction between such groups, or perhaps the merging of opposite groups into a single group which would be more or less equivalent to dissolved AlO.

Typical of positive effects are those of several elements on sulphur. Each atom of C, Al, Si, or P is probably bonded, like S, to a nearest-neighbour shell of iron atoms. Bonding of Fe atoms to C, Al, etc., leaves less Fe to be bonded to S and raises the activity coefficient of the latter. This competition for iron atoms increases the activity coefficient of each competing species so long as the effect is not overshadowed by stronger inter-solute attractive forces as in Fe–Al–O, Fe-C–O, and Fe–P–O solutions.

Wagner[40] has pointed out that, in addition to specific interaction between unlike metallic ions, the effects of solute atoms on the chemical potential of the electrons must be taken into consideration. The chemical potential μ_i of a metallic solute may be expressed as the sum of the chemical potential of its ions of valence z and that of the electrons

$$\mu_i = \mu_i\,(\text{ion}) + z_i \mu_e \qquad \ldots\ldots(23)$$

A change in the chemical potential of the electrons will affect the chemical potential of an electrically neutral component i for two reasons: (i) directly in view of the second term on the right-hand side of equation (23), and (ii) indirectly by a change of μ_i (ion) corresponding to a stronger or weaker interaction between positively charged metal ions and electrons when μ_e varies.

For the special case in which the only interaction effects are those due to positive metal ions and electrons, Wagner has shown that:

$$\varepsilon_s^{(s)} = \varepsilon_s^{(s)} = \pm \left[\varepsilon_s^{(s)}\varepsilon_s^{(s)}\right]^{\frac{1}{2}} \quad \text{.....(24)}$$

The square-root relation here is only an approximation, and it is significant only when $\varepsilon_s^{(s)}$ and $\varepsilon_s^{(s)}$ have the same sign; otherwise it is imaginary. The only test of this equation found in the data is not very satisfactory. For whilst $\varepsilon_C^{(Si)}$ is shown to be equal to $\varepsilon_{Si}^{(C)}$, both are considerably larger than $[\varepsilon_C^{(C)}\varepsilon_{Si}^{(Si)}]^{\frac{1}{2}}$.

The surprisingly large effect of S on $\log f_O$ may be ascribed tentatively to the combination of two effects. The first is the competition for iron atoms. It is postulated that a second contribution results from competition for electrons since both atoms probably diminish μ_e. This suggests, in view of equation (24), that the activity coefficient of O in binary Fe–O solutions ought to be reinvestigated with greater precision than was possible in the earlier studies.

It would be futile at this stage to attempt to differentiate in detail between the effects of inter-ionic attraction and of changes in the chemical potential of the electrons. Additional thermodynamic data are clearly needed to fill the blank spaces and to remove the uncertainties in an expanded Table I. It seems clear also that much must be learned by non-thermodynamic means concerning the structures of liquid metallic solutions before a complete understanding of these atomic interactions can be attained.

Acknowledgment

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References

1. C. WAGNER: "Thermodynamics of Alloys," p. 51: 1952, Cambridge, Mass., Addison-Wesley Press, Inc.
2. F. D. RICHARDSON and W. E. DENNIS: *Trans. Faraday Soc.*, 1953, vol. 49, pp. 171–180.
3. L. S. DARKEN and R. W. GURRY: "Physical Chemistry of Metals," pp. 406–410: 1953, New York, McGraw-Hill Publishing Co.
4. M. G. FONTANA and J. CHIPMAN: *Trans. Amer. Soc. Metals*, 1936, vol. 24, pp. 313–333.
5. S. MARSHALL and J. CHIPMAN: *Ibid.*, 1942, vol. 30, pp. 695–741.
6. H. C. VACHER: *J. Res. Nat. Bur. Stand.*, 1933, vol. 11, pp. 541–551.
7. G. PHRAGMÉN and B. KALLING: *Jernkontorets Ann.*, 1939, vol. 123, pp. 199–218.
8. For divergent views *see*:
   (*a*) P. HERASYMENKO: *J. Iron Steel Inst.*, 1947, vol. 157, pp. 515–525;
   (*b*) A. M. SAMARIN: *Izvest. Akad. Nauk S.S.S.R., Otdelenie Tekn. Nauk*, 1953, No. 8, pp. 1130–1136;
   (*c*) P. VALLET: *Rev. Mét.*, 1954, vol. 51, pp. 115–128.
9. "Basic Open Hearth Steelmaking," Chaps. 14 and 16: 1951, New York, A.I.M.M.E.
10. H. M. CHEN and J. CHIPMAN: *Trans. Amer. Soc. Metals*, 1947, vol. 38, pp. 70–113.
11. D. C. HILTY, W. D. FORGENG, and R. L. FOLKMAN: *Trans. Amer. Inst. Min. Met. Eng.*, 1955, vol. 203, pp. 253–268; *J. Met.*, 1955, vol. 7, Feb.
12. L. BREWER: *Chemical Reviews*, 1953, vol. 52, pp. 1–75.
13. A. D. MAH: *J. Amer. Chem. Soc.*, 1954, vol. 76, pp. 3363–3367.
14. K. K. KELLEY: *U.S. Bur. Mines Bull.*, 1949, No. 476; 1950, No. 477.
15. F. D. RICHARDSON, J. H. E. JEFFES, and G. WITHERS: *J. Iron Steel Inst.*, 1950, vol. 166, pp. 213–234.
16. "Selected Values of Chemical Thermodynamic Properties," ser. III: 1947 onwards, Washington, U.S. Department of Commerce, National Bureau of Standards.
17. E. T. TURKDOGAN: *J. Iron Steel Inst.*, 1954, vol. 178, pp. 278–283.
18. M. N. DASTUR and J. CHIPMAN: *Trans. Amer. Inst. Min. Met. Eng.*, 1949, vol. 185, pp. 441–445; *J. Met.*, 1949, vol. 1, Aug.
19. J. CHIPMAN and N. A. GOKCEN: *Trans. Amer. Inst. Min. Met. Eng.*, 1953, vol. 197, pp. 1017–1018; *J. Met.*, 1953, vol. 5, Aug.
20. N. A. GOKCEN and J. CHIPMAN: *Trans. Amer. Inst. Min. Met. Eng.*, 1953, vol. 197, pp. 173–178; *J. Met.*, 1953, vol. 5, Feb.
21. H. A. WRIEDT: Dissertation, 1954: Massachusetts Institute of Technology.
22. J. B. BOOKEY, F. D. RICHARDSON, and A. J. E. WELCH: *J. Iron Steel Inst.*, 1952, vol. 171, pp. 404–412.
23. D. C. HILTY and W. CRAFTS: *Trans. Amer. Inst. Min. Met. Eng.*, 1952, vol. 196, pp. 1307–1312; *J. Met.*, 1952, vol. 4, Dec.
24. M. N. DASTUR and J. CHIPMAN: *Trans. Amer. Inst. Min. Met. Eng.*, 1949, vol. 185, pp. 441–445; *J. Met.*, 1949, vol. 1, Aug.
25. F. D. RICHARDSON and W. E. DENNIS: *J. Iron Steel Inst.*, 1953, vol. 175, pp. 257–263.
26. W. E. DENNIS and F. D. RICHARDSON: *Ibid.*, 1953, vol. 175, pp. 264–266.
27. D. C. HILTY: *Trans. Amer. Inst. Min. Met. Eng.*, 1949, vol. 185, pp. 91–95; *J. Met.*, 1949, vol. 1, Feb.
28. J. CHIPMAN, R. M. ALFRED, L. W. GOTT, R. B. SMALL, D. M. WILSON, C. N. THOMSON, D. L. GUERNSEY, and J. C. FULTON: *Trans. Amer. Soc. Metals*, 1952, vol. 44, pp. 1215–1230.
29. J. CHIPMAN, J. C. FULTON, N. A. GOKCEN, and G. R. CASKEY: *Acta Met.*, 1954, vol. 2, pp. 439–450.
30. (*a*) J. P. MORRIS and A. J. WILLIAMS, jun.: *Trans. Amer. Soc. Metals*, 1949, vol. 41, pp. 1425–1439.
   (*b*) J. P. MORRIS and R. C. BUEHL: *Trans. Amer. Inst. Min. Met. Eng.*, 1950, vol. 188, pp. 317–322; *J. Met.*, 1950, vol. 2, Feb.
   (*c*) C. W. SHERMAN and J. CHIPMAN: *Trans. Amer. Inst. Min. Met. Eng.*, 1952, vol. 194, pp. 597–602; *J. Met.*, 1952, vol. 4, June.
31. J. A. CORDIER: Thesis, 1954: Massachusetts Institute of Technology.
32. J. P. MORRIS: *Trans. Amer. Inst. Min. Met. Eng.*, 1952, vol. 194, pp. 939–940; *J. Met.*, 1952, vol. 4, Sept.
33. H. LIANG, M. B. BEVER, and C. F. FLOE: *Trans. Amer. Inst. Min. Met. Eng.*, 1946, vol. 167, pp. 395–403; *Metals Technology*, 1946, vol. 13, Tech. Publ. No. 1975.
34. R. M. BRICK and J. A. CREEVY: *Metals Technology*, 1940, vol. 7, Tech. Publ. No. 1165.
35. L. EKLUND: *Jernkontorets Ann.*, 1939, vol. 123, pp. 545–556.
36. J. C. VAUGHAN, jun., and J. CHIPMAN: *Trans. Amer. Inst. Min. Met. Eng.*, 1940, vol. 140, pp. 224–231; *Metals Technology*, 1939, vol. 6, Tech. Publ. No. 1109.
37. W. B. HINCKE and L. R. BRANTLEY: *J. Amer. Chem. Soc.*, 1930, vol. 52, p. 48.
38. J. CHIPMAN: *Disc. Faraday Soc.*, 1948, No. 4, pp. 23–49.
39. (*a*) F. KÖRBER: *Stahl u. Eisen*, 1937, vol. 57, pp. 1349–1355.
   (*b*) F. KÖRBER and W. OELSEN: *Mitt. K. W. Inst. Eisenforsch.*, 1936, vol. 18, pp. 109–130.
40. C. WAGNER: *J. Chem. Phys.*, 1951, vol. 19, pp. 626–631.

Large Electric Furnaces

By D. F. Campbell, M.A., A.R.S.M., F.I.M.

SYNOPSIS

Large electric furnaces are replacing open-hearth melting equipment used for melting cold charges. This is due to the lower capital cost of the plant, and to reduced operating costs in certain countries. The paper describes the mechanical and electrical characteristics of U.S. and European large electric furnaces. The relative merits of various steelmaking processes must depend on many local conditions, but the rapidly rising price of producer-gas coal and the increasing efficiency of modern power stations are both favourable to the expansion of electric melting capacity. Small rapid producers of steel, such as special converters and electric furnaces, substantially reduce capital expenditure and make it possible to establish economic steelworks producing moderate outputs, which for many reasons are attractive in many countries. 1128

THE COMPARATIVE merits of different steelmaking processes are the subject of much controversy at the present time, but it is obvious that generalized conclusions are impossible, owing to the infinite variety of local conditions in regard to ore and fuel supplies and the manifold requirements of users of steel.

This paper is intended to throw light on the past, present, and future status of the large arc furnace as a producer of carbon and low-alloy steel in large quantities.

DEVELOPMENT OF THE ARC FURNACE

The use of arc furnaces for the production of 'tonnage' steel dates back to 26th May, 1909, when a 15-ton 2000-kW. furnace was put into operation at the South Works of the United States Steel Corporation at South Chicago.

This furnace was designed by Paul Héroult, and now almost every large arc furnace is of the same general type, having three vertical electrodes with approximately equilateral triangular spacing and a circular body. All large electric furnaces are now built on this principle and the three companies constructing these furnaces in the U.S.A. incorporate only minor modifications of mechanical design resulting from the great increase in capacity from 15 to 200-ton charges. The metallurgical characteristics are identical, and the similarity of design is apparent from an examination of Figs. 1–3.

The metallurgical performance of this first furnace was described in some detail in a paper* read before The Iron and Steel Institute in 1910. It was used for melting scrap, and also for refining acid Bessemer steel, but the latter operation was abandoned after some years' work, owing to the difficulty of conveying the liquid steel a considerable distance across a marshalling yard. At times, however, an output of 200 tons per 24 hr. was refined and cast into ingots low in sulphur and phosphorus.

Mechanical improvements have been made and electrical input increased, but other types of arc furnace have almost disappeared. A six-electrode furnace of over 100 tons capacity was built some years ago, but has not been repeated. This had an elliptical bath, and two three-phase transformers at either end.

Between 1911 and 1939, electric-arc furnaces were chiefly used for alloy-steel production and in steel foundries, but no great metallurgical development took place until top-charging and the use of oxygen were introduced.

PRESENT ELECTRIC-STEEL PRODUCTION AND PRACTICE

By 1952, arc furnaces were probably producing 15 million tons per annum of steel in the ladle. Table I shows the approximate tonnage of steel made in the principal steelmaking countries by the electric, open-hearth, and Bessemer processes. These statistics should be considered in the light of regional conditions.

In the U.K., the annual production of electric steel is over one million tons, most of which is high- or low-alloy steel, or mild steel for castings. There is in addition a moderate output of special irons for malleable treatment, or heat-resisting alloyed irons and of remelted swarf of high-quality iron.

The important question now confronting steelmakers is the scope of the electric-arc furnace as a steelmaking process, especially in regard to future steelworks. The choice must depend on local conditions of supply of raw materials, the qualities of steel required, the relative cost of power, coal, or natural gas, and the relative capital expenditure, but there can be no rule of universal application to find the answer.

It is in the U.S.A. that the best information is available for comparing the relative value of different steelmaking processes, but, in comparing the working costs of different processes in the U.S.A. and elsewhere,

* D. F. Campbell, *J. Iron Steel Inst.*, 1910, No. II, pp. 197–216.

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Table I

STEEL PRODUCTION IN 1952
In thousands of tons

	U.S.A.*	U.K.	France†	W. Germany	Italy	Luxem-burg	Belgium	Sweden†	India	Japan	Canada
Basic open-hearth	90,959	12,923	3379	7250	1804	...	627	504	1465	5839	3401
Acid „ „		1239						222	38		
Bessemer: Basic	717	887	6606	5687	195	2943	4212	128	...	210	...
Acid	...	439	74	...	...	...	...	31	...	...	4
Electric	9136	930	802	413	1505	58	162	740	52	960	866
Total production	100,812	16,418	10,861	13,350	3504	3001	5001	1625	1555	7009	4271
Percentage electric	9·1%	5·66%	7·4%	3·1%	42·9%	1·9%	3·2%	45·5%	3·3%	13·7%	20·2%

* U.S.A. statistics refer to plant capacity in 1953
† In 1952 Sweden produced 45,000 tons of sponge iron and France made 3900 tons of crucible steel

it must be borne in mind that the relative value of electricity, coal, oil, and natural gas, together with that of pig iron and scrap, is fundamentally different.

Capital expenditure is another matter of prime importance, especially in the case of new works or extension of capacity in existing melting shops.

The investigation recently made in the U.S.A. by fourteen electric utility companies and Bituminous Coal Research Inc. produced an exhaustive study of the capital and operating costs of open-hearth and electric melting shops, and it was concluded that the capital expenditure of an electric melting shop is about 60% of the capital cost of an open-hearth shop of similar capacity, in the case of works producing 250,000–500,000 tons per annum. This conclusion in regard to capital expenditure is applicable to other countries in regard to the relative costs of the two types of installation.

There are various considerations which favour works of this capacity in Europe, in preference to the vast U.S. works with outputs of 1–2 million tons per annum. These considerations are due partly to strategic and partly to political problems, whilst the increasing cost of transport favours dispersion of production. Tidewater sites are becoming increasingly important in European countries, where the export trade is important and most of the high-grade ores must be imported by sea.

The operating costs given in the U.S. report are applicable to a lesser degree to European or British Commonwealth conditions, owing to the great disparity in raw material and labour costs. Within the Commonwealth there are striking examples—e.g. coal in Glasgow costs four times as much per ton as coal of equal quality at steelworks near Vereeniging, South Africa.

United Kingdom

At the present time the production of electric steel in the U.K. of one million tons per annum is equal to that produced by the acid open-hearth process, and it seems certain that much of the steel made by the latter process, especially in foundries, could be more advantageously made in electric furnaces, with the exception of a small tonnage to meet some special specifications.

This change will probably take place in most cases where works melt cold metal on acid or basic hearths as the old furnaces become due for replacement or new melting shops are built. It is certainly advisable in the case of new shops, owing to the lower capital expenditure and the lighter cranes, and smaller shops, which can be used with 60-ton electric units melting and refining charges in half the time of the larger open-hearth units.

In the past the capacity of U.K. electric furnaces has been limited to 30 tons or less, but recently a 60-ton furnace has been successfully put to work in the Sheffield district. This installation, shown in Fig. 4, was made at the works of Samuel Fox and Co., Ltd., and is a Birlec-Lectromelt furnace rated at 15,000 kVA. The furnace is top-charged, has an inside shell diameter of 19 ft., and is provided with an austenitic steel bottom to enable a magnetic induction stirrer to be fitted at some later date. The furnace electrodes are of 20 in. dia.

'On-load' tap-changing gear enables the furnace voltage to be adjusted between a maximum of 325 V. and a minimum of 90 V. under load. The output of such a furnace making high-grade alloy steels under U.K. practice is about 5000–6000 tons per month.

France

In France, where Héroult built his first furnace in 1904, the production of electric steel has been favoured by low power cost, and the all-electric steelworks at Ugine have been an outstanding and successful example of a steelworks of which the prosperity is assisted by cheap hydro-electric power. In this works, self-baking electrodes are successfully used, as in the case of some Swedish works, with an economy of at least 40% of the cost of graphite. The cost of electrodes per ton of steel where graphite is used is about 17*s*. The use of self-baking electrodes in some European steelworks is probably the most important difference from U.S. practice.

The Perrin process developed at Ugine has accelerated production, and basic Bessemer metal electrically refined has been produced in large tonnages from

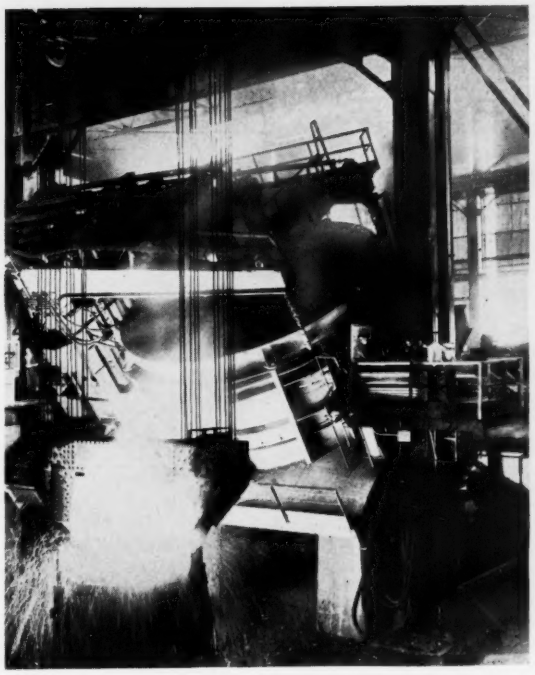


Fig. 1—200-ton Héroult furnace at McLouth Steel Corporation

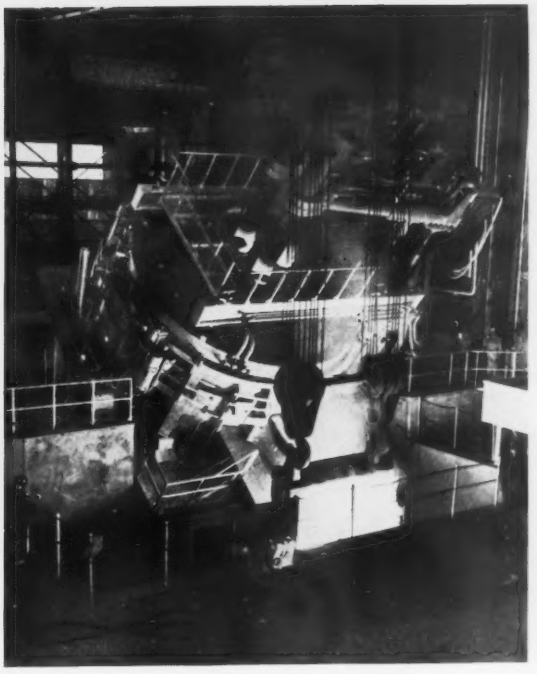
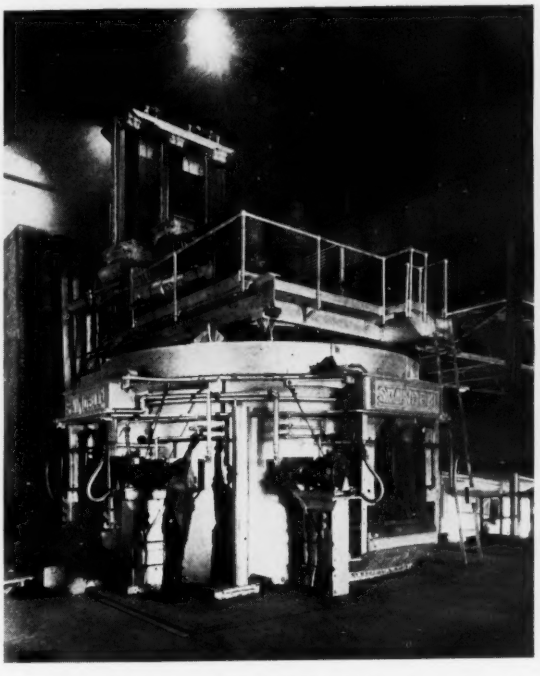
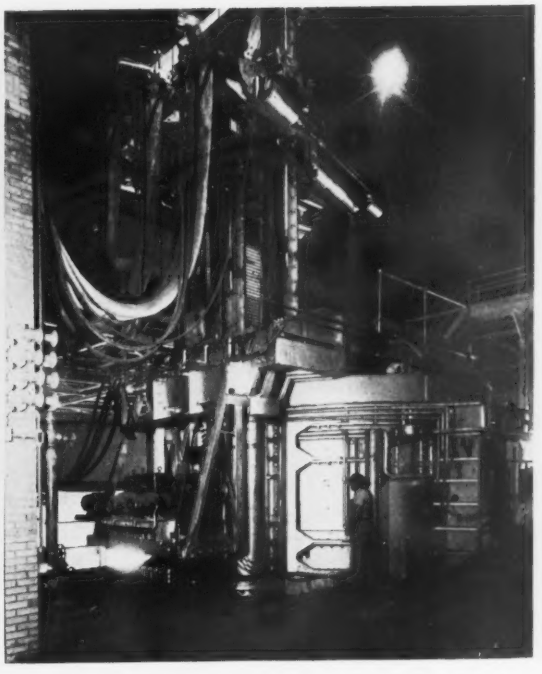


Fig. 2—100-ton Lectromelt furnace

(a)





(b)

Fig. 3—60–70-ton Swindell furnace: (*a*) charging side; (*b*) showing electrical connections

[*Campbe*
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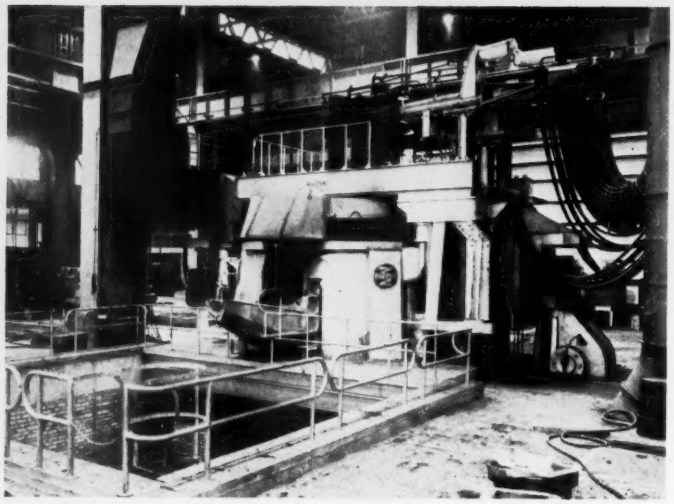

Fig. 4—60-ton Birlec Lectromelt furnace at Samuel Fox and Co. Ltd.

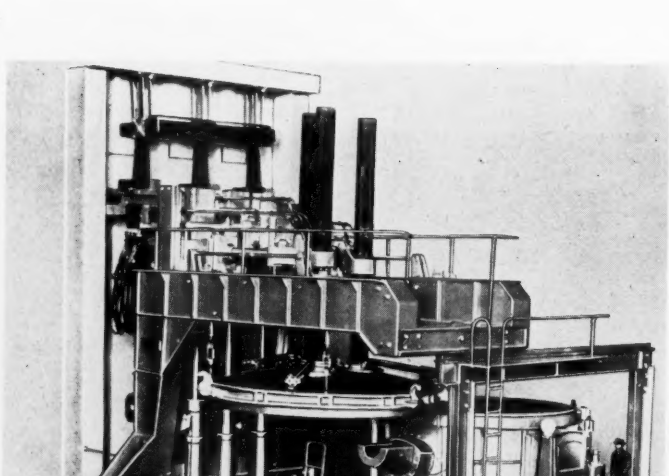

Fig. 5—40-ton ASEA furnace with traversing gantry

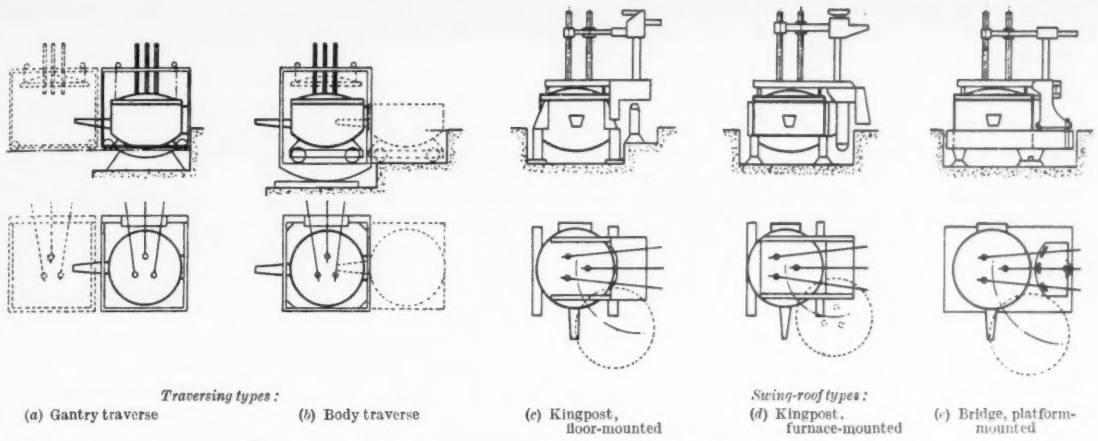

Fig. 6—Stages in development of removable-roof arc furnaces

furnaces of 25–30 tons, corresponding to the capacity of the basic Bessemer vessels. Recent improvements in the quality of basic Bessemer steel resulting from the use of special atmospheres, including oxygen, steam, and carbon dioxide, have eliminated the need for electric refining of certain qualities of low-carbon steel, and further development of these metallurgical processes is affecting the field of application of the open-hearth, basic Bessemer, and electric processes.

Sweden

In Sweden, electric-steel production has expanded rapidly, owing to the high cost of imported fuel, the availability of cheap power, and the high quality of products required.

Charcoal has become so expensive and scarce that the production of high-grade charcoal iron has been drastically reduced and, consequently, great efforts have resulted in the perfection of processes for the reduction of iron-ore concentrates to produce sponge iron as a raw material for electric furnaces in a country where scrap steel is expensive and solid and liquid fuel has to be imported. Thus, a good virgin raw material is available to replace the scarcity of scrap, to maintain the purity of Swedish steel, and avoid the risk of undesirable elements often contained in miscellaneous scrap.

This accounts for the great development of electric furnaces in Sweden up to sizes of about 45 tons capacity. A typical installation is shown in Fig. 5. This furnace has some unusual characteristics. The electrodes are hung from the shop roof structure. The furnace body is rotatable and also can be traversed into the charging bay. Self-baking electrodes are used, and carbon paste is charged into the electrodes from an upper platform. The electrodes are operated by A.S.E.A. hydraulic regulators, the switchgear is of air-blast type, and the transformer is of 10,500 kVA. with on-load tap-changing, giving a maximum arc voltage of 285 V.

This furnace is used for killed and rimming carbon steels; it melts a 45-ton charge in $3\frac{1}{4}$ hr. with a total energy consumption of 660 kWh. per ton in the ladle, and with a consumption of 17 lb. of Söderberg electrode per ton, costing 6*s*. 6*d*., or about one-third of the cost of graphite electrodes as used in the U.K. and the U.S.A.

Italy

In Italy, common qualities of steel are made in arc furnaces for tube manufacture, etc., but the hydro-electric supply has been unreliable, owing to lack of reservoirs and occasional drought.

In the past, there has been no domestic solid or liquid fuel available, but in recent years valuable deposits of natural gas have been found in the valley of the River Po, and the future relationship of electric and gas-fired furnaces in North Italy is difficult to forecast.

MECHANICAL CHARACTERISTICS OF LARGE ARC-FURNACE INSTALLATIONS

Charging

The mechanical structure of large furnaces originally consisted of simple furnaces tilted by hydraulic or electro-mechanical devices, and charged by open-hearth charging machines. Since it was impossible to charge sufficient light scrap in this way, the removal of the roof became necessary to permit basket charging.

This economical and convenient method of charging has necessitated further improvements in mechanical structure, owing to the great weight and cantileverage of large roofs.

For swing-roof furnaces two methods have been used. In the first, the roof is swung by independent hydraulic cylinders above the lifting cylinder, or king-post, on or adjacent to the furnace; in the second, the pivoting point is further from the furnace and part of the weight is taken on a carriage on a curved rail concentric with the pivot, as in the case of swing bridges. This gives a good mechanical design suitable for a heavy complicated cantilevered structure; the furnace body is not subject to the lateral strain which often causes distortion, and roof and body are easily repaired or removed. The principal stages in the evolution of removable-roof furnaces are shown in Fig. 6.

Swing roofs have resulted in great economy, as the charging time with cold scrap can be reduced from ½ hr. to a few minutes. An increase in the depth of body is also now common practice to give a large volume for light scrap charges.

Frequently the roof is removed, as melting proceeds, to add additional scrap, when light material has to be melted, and also for adding slag-making materials.

These furnaces are provided with everything necessary to ease the labour conditions for the operators, by the use of electrically or hydraulically-operated doors, but all equipment must be of very strong and rugged design, as light charges are sometimes levelled with ' tups ' or by swinging the roof.

In one U.S. steelworks, where nine large furnaces have been operated since 1943, the change to top-charging, coupled with an increase of transformer capacity from 12,000 to 20,000 kVA., resulted in an increase of 70–80% of output.

Top-charging is essential for efficient production, and the swing roof is the most economic method, in regard to capital expenditure, foundations, and floor space. Top-charging saves much time and utilizes the residual heat in the refractory lining, whilst electrode consumption is reduced, because during door-charging much air enters the furnace when the electrodes are at a high temperature, causing rapid burning. Electrode costs are one of the most important items in electric-furnace operations, and possibly the only one where substantial future savings may be made.

Slagging

Slagging practice varies in different works but, as this involves the hardest manual labour in many melting shops, it is important. Electromagnetic devices are now available, notably the A.S.E.A. stirrer, which brings the slag towards the slagging door and so facilitates the pouring and skimming of the slag. Another method used in some works consists of pouring the complete charge into a ladle, allowing the slag to overflow the ladle, and returning the steel to the furnace for final deoxidation. Both these methods have the advantage of mixing thoroughly the bath, which is important in the case of highly alloyed steels.

Size

It would appear that the optimum size of arc furnace for a steelworks producing 250,000–500,000 tons of steel per annum is a unit having a body diameter of 18–22 ft. and a transformer capacity of 16,000–20,000 kVA.

Larger furnaces and higher transformer ratings do not seem economic for many reasons, and the capital expenditure increases rapidly for cranes, buildings, etc., if larger units are used, whilst greater inputs of energy may be costly, owing to maximum-demand payments and power-factor difficulties. There is also a limit to the speed at which ingot moulds can be economically handled. If the continuous casting of blooms and slabs becomes common practice, comparatively small and frequent casts are certainly preferable.

In modern high-powered furnaces, more water-cooling is being used, and water-cooled roof rings are becoming general practice.

ELECTRICAL EQUIPMENT

In the case of electrical equipment, the tendency of development in Europe differs somewhat from that of the U.S.A.

Switchgear

The control of large arc furnaces imposes a heavy duty on the switchgear and calls for a particularly robust design.

For the medium-sized arc furnaces, British and U.S. practice differs fairly widely. In the U.K. the general tendency is to use an oil switch; provided that the switch is robust enough mechanically, little difficulty is experienced, apart from the necessity for maintenance of oil and contacts. In the U.S.A. there is a general tendency to avoid the use of oil wherever possible, and suitable designs of air-break switchgear are available and generally used, with rupturing capacities up to 500 MVA. at 15 kV.

For many arc furnaces the air-break type of switchgear is adopted in the U.S.A. where its rating is suitable, but for the largest furnaces air-blast switchgear is considered necessary. In the U.K. air-blast switchgear has also been used for the larger furnaces and this design has much to commend it for this duty. The operating parts of the switch are comparatively light and it is therefore able to withstand heavy duty more easily, since there is less wear and tear on the mechanism and there is, of course, no oil to carbonize.

It should be remembered that a switch designed for distribution service, unless particularly robust, is not usually suitable for arc-furnace control. A distribution switch will be called upon to operate perhaps several hundred times per year, whereas the switch controlling an arc furnace is frequently operated 15,000–20,000 times in the same period. The number of operations is influenced by the type of tap-change gear fitted to the transformer and the figures quoted apply to off-load switching. With on-load switching of the transformer tappings, the duty on the switch is reduced by about half.

In earlier installations of air-blast switchgear in the U.K. some difficulty was experienced at first from surge voltages caused by the very rapid breaking of the switch; however, this difficulty has been overcome by suitable design, and surge diverters are now usually installed, particularly for the higher supply voltages (e.g. about 33 kV.).

In general, the air-blast switch is more expensive than an oil circuit-breaker, so that its use is generally confined to the larger furnaces and higher supply voltages, where its technical advantages over the oil switch make it especially desirable.

Transformers

The arc-furnace transformer also has to be suitable for heavy duty. During the melting period the load fluctuates rapidly, giving rise to impulsive mechanical stresses in the windings, and the frequency of occurrence and magnitude of voltage surges are greater with an arc-furnace transformer (and its associated reactor) than in normal distribution service. This

requires the windings and heavy current connections to be adequately braced and the insulation suitably reinforced.

In the larger size of transformer, a water-cooled design is usually preferable, since it economizes in space and avoids the necessity for ventilating the transformer chamber with large quantities of air, involving expensive ventilation equipment. In the U.K. the preferred design for large transformers is the forced-oil-circulated water-cooled type (B.S.S. type *OFW*). In the U.S.A. the general preference in the past has been for the older plain water-cooled type (equivalent to B.S.S. type *OW*), in which the heat is removed from the oil by means of a cooling coil in the top of the transformer tank. The forced-circulation type, in which the oil is pumped through an oil/water heat exchanger, is now gaining favour in the U.S.A. With this design, it is possible to reduce the size of the transformer even further, as compared with the plain water-cooled type. With a large arc furnace, the transformer design is slightly simplified, as compared with the transformers feeding smaller furnaces, since above a rating of about 10,000 kVA. the use of an additional reactor is usually no longer necessary. In fact, for ratings appreciably higher than 10,000 kVA. the problem is one of keeping down the reactance of the transformer and low-voltage connections generally, as otherwise the secondary voltage of the transformer has to be increased, in order to get the power into the furnace at a reasonable power factor. The problem is slightly less acute in the U.K., as compared with the U.S.A., on account of the lower standard frequency of supply at 50 cycles, which causes a natural reduction in reactance. As an example of a typical large installation, a furnace recently commissioned in the U.S.A. has a rating of 33 MVA. and a maximum secondary voltage of 550 V. (between electrodes). This furnace has a 24 ft. 6 in. dia. shell and normal charges are 200 tons weight.

A very rough rule which assesses the approximate rating of large furnaces is 1000 kVA. per foot of diameter at about 18-ft. dia. shell, rising to about 1250–1400 kVA. at 24-ft. dia.

Tap-Changing Gear

Hitherto the control of the tappings of an arc-furnace transformer has mainly been by an off-load tap switch. This is certainly true in the U.S.A. where, apart from certain special applications such as ferro-alloy furnaces and graphitizing furnaces, neither of which are true arc furnaces, no on-load tap-change switches have been used up to the present.

In the U.K. also off-load switching has been customary, apart from one recently installed large furnace. Whilst the size of the furnace remained comparatively small, off-load switching did not have a particularly adverse effect upon operation, but with larger furnaces two points have to be considered. Firstly, with the larger furnace the reactor can be omitted, and this makes the application of on-load tap-changing much simpler from the technical aspect. Secondly, the effects on the supply system of switching large blocks of load are considerably greater, and this makes the introduction of on-load tap-changing most desirable. This is particularly true in the Scandinavian countries, where an arc-furnace load may be a large proportion of the total load on a small hydro-electric power station or at the end of a long transmission line. With off-load tap-changing, it is necessary to open the furnace switch and close it again, after a comparatively short time when the tap-change has been carried out. This can be a serious embarrassment to the supply system.

A disadvantage of the on-load tap-change switch is that the switching duty, and therefore the maintenance, is divided between the switch controlling the furnace and the diverter switches in the tap-changing gear. However, particularly where the grade of steel being melted is one that does not require a long refining period, the introduction of on-load tap-change gear can result in an appreciable increase in the production from a furnace and may make this introduction very well worth while.

In Europe there are some smaller furnaces with on-load tap-change switches, but usually the reactor is separate and equipped with its own separate tap-change switch. Such a system demands greater skill and care on the part of the operator to produce satisfactory results.

Regulators

To review all possible types of arc-furnace regulators would take a long time. After a period of development over many years evolving from the old impulse-type regulator, through the contactor type and 'balanced beam' types, both in the U.S.A. and the U.K. the electric type now most used is that covered by the generic term 'rotary regulator.' This term includes many variants (e.g. Rototrol, amplidyne, Regulex, Rotodyne, etc.) largely differing in detail only.

One of the advantages of this type of regulator is its rapid response and ease of maintenance. In cases where this type of regulator has replaced some of the earlier ones, the reduction in maintenance has been very significant.

Basically the principle is that of rectifying the arc current and applying this, together with the arc voltage (also rectified), in opposition, to the excitation of a generator, which in turn is connected to the electrode motor. An increase in current, or decrease in voltage, causes the generator to develop a voltage of one polarity, causing the electrode-raising motor to raise the electrode, whilst a decrease in current, or increase in voltage, has the opposite effect. This principle of balancing current against voltage has been used with other types of regulator in the past and has been proved to be the most desirable system of control.

Hydraulic regulators have always been more popular in Europe than the U.S.A. over past years, though one make of hydraulic regulator has now made its appearance in the U.S.A. It is claimed that with a hydraulic regulator more rapid response and higher speeds are possible. Whilst this may be true, it is equally true that adequately satisfactory results can be obtained with electric regulation, since the main limitation of rate of response is mechanical inertia of the parts of the furnace associated with the support of the electrodes.

Counterbalance

There has been discussion in the past on whether or not to counterbalance the electrodes in the interests of rapid response. Although at first sight the omission of counterbalance weights would appear to offer an advantage in that the mass to be moved is less, the converse is actually true. Without counterbalance weights, the greatest acceleration and speed will occur in a downward direction, whilst in order to clear short circuits, etc., the acceleration and speed in the upward direction is the important factor. It can be shown that if a furnace not fitted with counterbalance weights is so fitted, provided that the size of electrode-raising motor is not changed, the acceleration and speeds can be increased simply by fitting balance weights.

Bus-Bar and Cable Connections

The connections between the transformer and the furnace can have an important effect upon the reactance, and must be considered in relation to the size and characteristics of the furnace.

For small furnaces there is no particular advantage in elaborate design of bus-bar system to achieve a low reactance, but for a large furnace this point requires careful attention since, as has been previously stated, in the larger size of furnace the reactance of the bus-bar system has to be kept to a practical minimum to avoid increasing the furnace voltage.

Low-voltage bus-bar runs are usually carried out in naturally cooled rectangular-section copper bars. With a large furnace, to minimize reactance both ends of the phase windings of the transformer are often brought to a point as near the furnace as possible and the delta connection is carried out at that point. This involves the use of rather more copper than if the line leads only were brought through, as would be the case with a smaller furnace.

A preferred alternative is a group of water-cooled tubes, though it is not quite so easy to obtain a low reactance system with this design. It results in some economy in weight at the expense of a slight increase in loss. This increase, however, is usually insignificant in relation to the power of the furnace.

For the cable connections between the bus-bar ends and the furnace, groups of air-cooled cables are almost universally used. Some attempts have been made to use water-cooled cables, particularly in the U.S.A., but experience with these shows that the arrangement is not very satisfactory from the maintenance aspect, and there is now a tendency in the U.S.A. to revert to the air-cooled cables.

Energy Consumption

Of the energy consumed about 76% is found in the molten metal and slag, or used in metallurgical heat balance, as compared with 30% in the case of cold-charged open-hearth furnaces. The loss is approximately as follows:

	Electric	Open-Hearth
Total losses as percentage of heat input	24%	70%
Radiation, walls, roof	10–11%	28%
Water-cooling	4%	5%
Gases	2·5%	27·5%
Evaporation of water in air and charge	...	8·5%
Electrical losses	7–8%	...

The high cost of electrical heat counterbalances the advantage of the high efficiency of the electric furnace.

SPACE FACTOR

It may be of interest to give some information on the space factor of an electric and an open-hearth melting shop producing 500,000 tons per annum. The space occupied by electric and open-hearth furnaces has an important bearing on capital expenditure. In a well-known works in which each open-hearth and electric unit has approximately the same weekly output, the length of shop required for four open-hearth furnaces is approximately 600 ft., served by a 350-ton crane. A shop equipped for four electric furnaces of 70 tons, however, is 400 ft. long and equipped with cranes of 150 tons lifting capacity.

In this connection, the actual dimensions of two large U.S. melting shops, including space for roof repairs and ladle heating, may be mentioned. In one shop 560 ft. long, equipped with a 125-ton casting crane, there are five 70-ton furnaces melting cold charges, and space is allowed for casting pits, roof repairs, electrode storage, etc. In another building, 1470 ft. long, four large tilting open-hearth furnaces occupy 604 ft., and nine 70-ton arc furnaces the remaining 866 ft., the open-hearths requiring 350-ton casting cranes and the electric furnaces cranes of 150 tons lifting capacity.

The most recent installation of large arc furnaces in the U.S.A. is of two Héroult furnaces of 24 ft. 6 in. dia., equipped with transformers of 30,000 kVA. These furnaces cast a 200-ton heat.

In certain cases, the furnaces are used to make the commonest qualities of semi-killed carbon steel, and some remarkable results are claimed. For example, 150-ton heats in 22 ft. dia. furnaces with 36,000-kVA. transformers are producing 35 tons/hr. at a power consumption of 500–550 units per ton. In the case of a 20-ft. furnace with 25,000 kVA., over 14,000 tons have been produced in a month of 26 operating days. It would appear that the transformers may be of greater kVA. capacity than is necessary or economical.

THE FUTURE OF ELECTRIC STEELMAKING

Having reviewed recent improvements in large arc furnaces, the question arises how far can this method of steelmaking compete with the improved open-hearth and Bessemer processes, which have made such rapid progress in the last few years by the injection of oxygen or oxygen-enriched and other controlled atmospheres.

In the case of existing large modern open-hearth steelworks using a large percentage of liquid iron, arc furnaces are not justified, but in the case of new melting shops, capital expenditure, flexibility, and adaptability to varying circumstances might favour electric or Bessemer–electric melting shops.

A reduction of 40% or more in capital expenditure, and a saving in operating costs, by pouring 50-ton charges frequently, especially when making continuously cast blooms or slabs, might well justify an electric melting shop, but whether the steel should be made in controlled-atmosphere converters or electric-arc furnaces, or both, is a question for careful consideration when all the local data of cost and quality of raw materials are available.

There is, however, no doubt that there are a great number of the older furnaces melting cold stock that must soon be replaced by electric furnaces which operate at much higher speeds.

In all countries the relative cost of pig iron and scrap, the percentage of scrap to be used, and the cost of power and competitive fuel are essential factors in selecting a steelmaking process. It is highly significant for the future that in the U.K. the cost of electric power has doubled during the last 15 years, whereas the cost of coal has more than quadrupled in the same period. There seems, moreover, to be every indication that this very marked trend in favour of the arc furnace is likely to continue.

The Operation of a 60-Ton Arc Furnace

AT SAMUEL FOX AND CO., LTD.

By R. Wilcock, A.Met., F.I.M.

SYNOPSIS

A 60-ton arc furnace has been installed by Samuel Fox and Co., Ltd., Stocksbridge, mainly for the production of high-grade alloy steels. This note gives a brief description of operating experience during the first few months of production. 1134

THIS PAPER is a preliminary note on the new 60-ton arc furnace at Samuel Fox and Co., Ltd., Stocksbridge. It is hoped to publish a fuller report later.

The furnace was built by Birlec Ltd., under licence from the Pittsburgh Lectromelt Furnace Corporation, the design following current U.S. practice for large furnaces. It is a top-charged direct-arc tilting furnace with three 20-in. dia. graphite electrodes connected to a 15,000-kVA. transformer which is fitted with 'on-load' tap-changing. The casing is 19 ft. inside diameter. A photograph of the furnace tapping into the ladle is shown in Fig. 1.

The roof, which is suspended at four points, is lifted and swung clear by the action of a robust hydraulic ram so that the top-charging can be carried out. The larger additions of ferro-alloys are made using a diesel-hydraulic ground charger (*see* Fig. 2). The tilting of the furnace is to a maximum of 40° forward and 15° backwards, again operated hydraulically.

OPERATING EXPERIENCE

The first charge in the furnace was tapped early in November, 1954, and the furnace has since been worked, originally on the basis of one cast per day, and later stepped up to full three-shift working. Up to the beginning of March, 1955, rather more than 200 casts have been made. One or two of these were plain carbon steel, but the majority have been high-grade alloy steels such as 1% C–Cr ball-bearing steel and alloy structural and alloy case-hardening steels.

The total weight charged was originally 62 tons, but this has gradually been increased to 70–71 tons, yielding 65–68 tons of ingots. Basic scrap and pig iron are used and usually provide a full furnace charge from two baskets only, although occasionally when very bulky scrap is used three baskets are necessary. A high percentage of turnings is used (up to 30%), the amount being limited to this by the likelihood of excessive heat being generated from the entrapped oil and causing overheating of the fume-extraction plant if greater amounts are used. The charge is adjusted to give a 0·25–0·30% carbon boil, the carbon, if necessary, being added in the form of acid pig iron. Care is taken in the selection of scrap to reduce contamination by 'tramp' elements such as copper or tin.

So far the sulphur and phosphorus contents of the charge on melting have not been high, only isolated examples giving above 0·05% of either element; this has to some extent helped to give good output rates. On nickel-bearing steels some of the virgin nickel is added with the basket charge, and full use is made of alloy-bearing scraps largely arising from the Company's own mills. Sufficient limestone is charged in the baskets to give a good melting slag.

A typical week's run with the furnace working continuously is shown in Table I. The average tap-to-tap times are considerably affected by the slow working at the beginning of the week.

MELTING

Melting is started on a tapping of 208 V., working up gradually to the full power at 325 V., when the

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Table I

OUPUT AND POWER CONSUMPTION OF 60-TON FURNACE

Cast No.	Quality	Melting Time hr. min.	Oxidizing Time hr. min.	Reducing Time hr. min.	Total Time hr. min.	Tap-to-Tap hr. min.	Power Consumption, units			Charged Weight tons cwt. q.	Ingot Weight tons cwt. q.
							Melting	Refining	Total		
A.158	1¼% Ni–Cr–Mo	4 52	4 25	1 35	10 52	...	33,300	18,100	51,400	69 7 0	65 15 1
159	1% C–Cr	4 09	3 55	1 56	10 00	11 25	33,800	17,100	50,900	69 10 1	65 11 2
160	1% C–Cr	4 32	0 47	1 28	6 47	7 35	32,200	10,400	42,600	69 12 1	65 15 3
161	2¼% Cr–Mo	4 20	1 43	1 42	7 45	8 20	31,600	10,300	41,900	68 16 2	65 15 1
162	2¼% Cr–Mo	4 04	2 55	2 06	9 05	9 40	32,600	12,900	45,500	69 6 2	65 14 2
163	1¼% Ni–Cr–Mo	3 35	2 45	1 47	8 07	8 37	31,100	13,100	44,200	69 9 0	66 6 2
164	1¼% Ni–Cr–Mo	3 17	1 05	1 38	6 00	6 41	30,000	10,200	40,000	70 3 2	65 15 1
165	1¼% Ni–Cr–Mo	3 26	1 46	1 51	7 03	8 05	31,700	12,900	44,600	70 0 0	65 16 2
166	1¼% Ni–Cr–Mo	3 55	2 20	1 22	7 37	8 24	32,300	11,600	43,900	69 6 2	65 14 2
167	1¼% Ni–Cr–Mo	4 15	1 26	1 35	7 16	8 04	34,000	9300	43,300	69 13 1	65 11 1
168	1¼% Ni–Cr–Mo	3 29	1 16	1 47	6 32	7 25	31,700	11,300	43,000	70 1 0	65 17 0
169	1¼% Ni–Cr–Mo	4 24	2 10	1 16	7 50	8 30	35,400	9200	44,600	69 11 1	65 14 3
170	1¼% Ni–Cr–Mo	3 28	1 34	1 34	6 36	7 20	31,500	11,100	42,600	70 11 2	65 2 0
171	3% Cr–Mo	4 33	1 56	1 43	8 12	8 51	30,900	14,500	45,400	68 9 1	63 19 2
172	2% Ni–Mo	3 25	1 28	1 02	5 55	6 23	30,700	8400	39,100	68 17 1	63 12 3
173	1¾% Ni–Cr–Mo	4 00	1 45	1 30	7 15	7 45	32,300	10,700	43,000	69 13 3	65 11 2
174	1¾% Ni–Cr–Mo	3 49	1 27	1 37	6 53	7 28	31,700	11,700	43,400	69 12 2	65 14 2
	Mean	3 58	2 02	1 37	7 38	8 10	32,165	11,929	44,094	69 10 3	65 9 3

	tons	cwt.	q.		
Total charged weight	1182	1	1	Metallic yield	96·9%
Total ingot weight	1113	8	1	Ingot yield	94·2%
Total scrap weight	32	8	0		

electrodes are well into the scrap. Using the full input of 15,000 kVA. the consumption is approximately 12,000 kW. When the first basketful of scrap has been partly melted, the second basket is charged and the arcs are struck again at 208 V., working up to full power at 325 V. During the working of the charge after fully melting, voltages ranging from 208 to 125 V. are used, with a power consumption of 2000–6000 kW.

The consumption of electricity during one week is shown in Table I. The average consumption, at 674 units per ingot ton, compares favourably with average figures of 832 and 829 units per ingot ton on two 12½-ton furnaces.

Carbon removal has in general been effected by using ore; when making low-carbon heats ore is charged in the second basket, but mostly it is fed subsequently, during the working of the charge. The use of ore, however, is being replaced by oxygen lancing; oxygen is supplied from a 2-in. pipeline at a pressure of 150 lb./sq. in. and a rate of about 600 cu. ft./min.

Owing to the fairly low phosphorus content of the melts, little trouble has been experienced in removing phosphorus, although it is desirable when making the class of material produced in the furnace to have only about 0·010% remaining in the metal when removing the oxidizing slag, so as to allow for some phosphorus reversion during the reducing period. When the phosphorus contents on melting are high, two or three complete or partial removals of the slag are necessary to achieve this end. With earlier melts, phosphorus reversion to the extent of 0·010% was experienced during the reducing-slag period, essentially owing to the difficulty in removing the last traces of slag from such a large furnace. An adequate technique has now been worked out, and phosphorus reversion on this furnace is essentially similar to that on the smaller furnaces, as shown by Table II.

When the furnace was built, it was fitted with austenitic-steel bottom plates to permit the installation of an A.S.E.A. electromagnetic stirrer; this should be installed during 1955, and is expected, apart from other advantages, to ease slagging-off. At present about 18 min. of hard work is needed to get efficient removal of all the slag (*see* Fig. 3).

REDUCING SLAG AND DEOXIDATION

After removal of the oxidizing slag, the bath is deoxidized by the addition of ferrosilicon to give about 0·2–0·3% silicon in the metal. The reducing slag is then applied using limestone and fluorspar in the ratio of roughly seven of limestone to one of spar, with crushed anthracite or crushed electrodes added as needed for reducing the metal oxides and so giving a good white falling slag. This arc-furnace practice uses limestone to the exclusion of burnt lime, so as to avoid, as much as possible, the introduction of moisture to the furnace. This does not matter very much in the early stages when in any case the scrap is sometimes wet when charged, but it is of particular importance during the reducing period, when there is no carbon boil to remove hydrogen thus introduced into the metal. Similarly, precautions are taken to dry thoroughly all slag-making and alloy additions used in the later stages of steelmaking; two electric furnaces were specially installed to roast the ferro-alloys at 650° C. to remove hydrogen.

No difficulty has been experienced in desulphurization, but, owing to the comparatively deep bath, the rate of desulphurization has tended to be very slightly slower than in the 12½-ton furnaces.

It was believed that tapping the furnace in such a way that a good proportion of the slag was poured into the ladle quite early, resulting in the slag and metal being well mixed, would give a little extra desulphurization after leaving the furnace. The results obtained so far from bath and pit samples do not, however, confirm that this practice achieves any significant removal of sulphur; this is shown in Table III.

Fig. 1—Furnace tapping

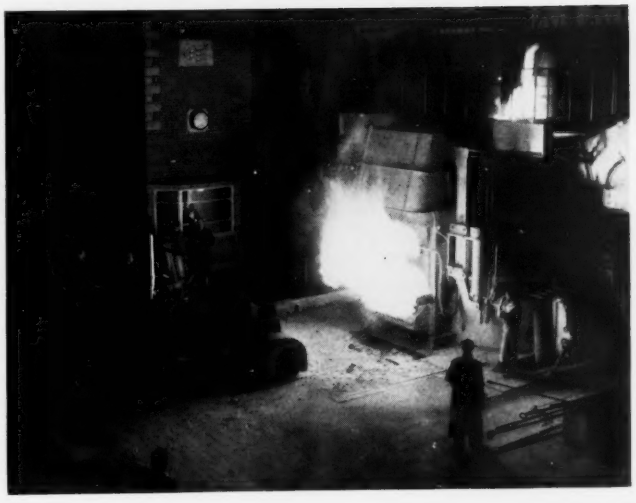

Fig. 2—Floor charger in action

Fig. 3—Slagging operation

Table II

PHOSPHORUS REVERSION: COMPARISON OF 60-TON AND 12-TON FURNACES
1% C–Cr and 1¾% Ni–Cr–Mo Qualities

	60-ton Furnace				12-ton Furnace
Cast numbers	1–50	51–100	101–150	151–200	...
Number of casts	35	34	35	44	20
Number of casts showing phosphorus reversion	24	26	17	12	10
Average increase in phosphorus of casts showing reversion, %	0·005	0·005	0·004	0·003	0·002
Maximum increase in phosphorus content, %	0·011	0·013	0·017	0·006	0·005

PIT PRACTICE

The steel is normally teemed uphill from a double-stoppered ladle into 40-cwt. wide-end-up ingot moulds set in clusters of three or five. If the ingots are not to be hot-charged to the soaking pits for rolling, they are cooled slowly in refractory-lined pits until they have reached a temperature of less than 300° C., an operation which takes about three days.

TEMPERATURE CONTROLS

Metal temperatures are obtained by quick-immersion pyrometers, indicated on a 20-in. dia. illuminated Tinsley indicator mounted on the wall of the control cabin, the temperature being simultaneously recorded on a Tinsley recorder. Regular use is made of this equipment during the working of the heats.

In addition, there are various other temperature indicators measuring, for instance, the temperature of the cooling water, but the only instrument worthy of further comment is one located in the Visco dust-extractor duct. In accordance with what is becoming standard practice in the U.K., the furnace is fitted with hoods for removing the large amount of dust and fume produced, the exhaust gases being subsequently passed through natural-fibre filters. Under some conditions, as for instance when oily turnings have been charged, these exhaust gases can become very hot in spite of water-cooling incorporated in the system, giving rise to some danger of burning out the filters. The pyrometer is therefore linked with the exhaust fans, cutting them out if the temperature rises to danger level. The natural-fibre filters will probably be replaced by filters of synthetic material, which will withstand higher temperatures.

ELECTRODE CONSUMPTION

A certain amount of trouble has been caused by the 20-in. electrodes cracking at the collar. This trouble has been greatly reduced by strengthening the collar by using $10\frac{3}{8}$-in. dia. nipples in place of the $11\frac{13}{16}$-in. dia. ones originally used. The position is at present still not satisfactory, even with the introduction of mechanical jointing of the electrodes away from the furnace instead of the usual hand-jointing *in situ*. Tapered nipples as normally used in the U.S.A. for large electrodes will probably be an advantage compared with the parallel pattern, which are the only ones available in the U.K.

The figures for electrode consumption, although better than at the start of operations, are still adversely affected by pieces breaking off. The consumption for the week shown in Table I was 17·94 lb. per ton of ingots produced; this compares unfavourably with the two smaller furnaces, using 12-in. graphite electrodes, typical figures for which are 15·15 and 13·05 lb. per ingot ton.

Table III

EFFECT OF SLAG/METAL MIXING DURING POURING INTO LADLE ON SULPHUR CONTENT

Cast No.	Quality	Bath-Sample S, %	Time between Bath Sample and Tap, min.	Estimated S at Tap, %	Pit-Sample S, %	Loss of S in Tapping, %	Apparent Mixing of Slag and Metal in Ladle
A.56	1% C–Cr	0·026	1	0·026	0·027	...	Poor
A.67	Mn–Cr	0·024	2	$0·023_5$	0·024	...	Good
A.79	1¾% Ni–Cr–Mo	0·021	9	$0·015_5$	0·014	$0·001_5$	Good
A.87	1% Cr–Mo	0·025	9	0·021	0·018	0·003	Fairly good
A.104	1¾% Ni–Cr–Mo	0·022	3	0·021	0·024	...	Fairly good
A.112	1¾% Ni–Cr–Mo	0·022	1	0·022	0·023	...	Good
A.138	1% C–Cr	0·026	4	$0·025_5$	0·027	...	Fairly good
A.147	1¾% Ni–Cr–Mo	0·019	4	0·018	0·015	0·003	Fairly good

REFRACTORY PERFORMANCE

Fettling time has been about 18–20 min. per heat, the consumption of dolomite being approximately 25 lb. per ton of ingots (this compares with 40 lb. per ingot ton for the 12½-ton furnaces). The hearth is still in good condition.

The performance of the side walls has been very satisfactory. The furnace does not work during weekends and advantage is usually taken to do some patching, but it was not necessary to rebrick the walls completely until after 13 weeks' operations. The taphole is normally patched every weekend, and is rebricked every three weeks.

The intermittent working of the furnace at the start of the campaign would be expected to have a deleterious effect on the life of the roof, and the first one lasted only 55 heats. Performance subsequently has improved, however, the second roof lasting 74 and the third 92 heats.

QUALITY OF STEEL PRODUCED

The billets produced from this furnace have been, so far as can be determined on a few months' working, very similar to those from the 12½-ton furnaces, which form the only basis for comparison. Yields of good billet have been very similar.

It is obviously too early to be able to make any definite statement about metallurgical quality at this stage, as a complete assessment involves the performance of the material at customers' works and in service. A little of this information has come through and is confirming the results of preliminary laboratory work that the quality is very similar in all respects to that of the smaller arc furnaces.

Acknowledgments

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Observations of Stainless Steel Melting Practice

By D. C. Hilty, H. P. Rassbach, and Walter Crafts

SYNOPSIS

Melting practice for stainless steels is reviewed and rationalized with theoretical considerations to provide the bases for prediction and control of the process and the design of the most economical practices. A further refinement of the relations among chromium, carbon, and temperature, and an evaluation of the thermal balance during the oxidizing period are described. Relatively high rates of oxygen input and higher temperatures prior to injecting oxygen are indicated to minimize metallic oxidation and oxygen consumption during decarburization.

Recovery of oxidized chromium, manganese, and iron from the slag is shown to depend on the chromium and silicon contents of the metal, the basicity of the slag, and upon temperature and mechanical factors that may affect the rate of approach to equilibrium. Effective recovery may be hampered by mechanical factors such as stratification of the bath and can be greatly improved by thorough stirring or reladling of the melt.

Residual nitrogen content may vary throughout the course of a heat but tends to approach a final value consistent with the chromium content of the steel. Sulphur may be lowered readily under basic and reducing slag with silicon present in the metal. Oxygen content is indicated to depend principally on temperature and composition of the bath regardless of practice or type of ferrochromium additions. 1109

STAINLESS STEEL PRODUCTION over the past 20 years has increased ten-fold to 1,000,000 tons per year in the U.S.A. alone. This growth has resulted from development of steels with useful properties and from many advances in the art of economical steelmaking. Gaseous oxygen injection has facilitated remelting of scrap and, assisted by lower carbon ferrochromium alloys, has made practical the production of very low-carbon steels with better corrosion resistance. Larger and more highly powered arc-furnaces together with enlarged oxygen-supply systems have materially improved methods of production. Studies of the underlying chemistry and the practical art have been pursued intensively in laboratories and melting shops in order to develop improved practices. However, the existing wide variations in practice indicate that many problems in the process require clarification.

The range of furnace sizes employed for melting stainless steel extends from those having a capacity of less than 1 ton to those of 80 tons and more. Power input per ton, voltage range, thermal characteristics, and the mechanical design of these furnaces vary considerably. During the past ten years there has been a trend to higher power input per ton and to substantially higher voltages. The removable roof adapted to top-charging has gained wide acceptance, because of the advantage of rapid charging of metal, ferro-alloys, and fluxes.

The basic hearth is used for the major part of the total tonnage of stainless steel in order to facilitate control of composition and improve recovery of metallic values. The chromite hearth is used to a limited extent, and the acid hearth is found mostly

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in foundry operations where small furnaces are required.

Scrap charges for a specific grade of stainless steel may vary considerably in concentration of chromium, carbon, and silicon. A primary consideration in establishing a charge practice is to make use of revert scrap and thereby recover valuable metallics such as chromium and nickel. In general, the chromium content of the charge for the grades of stainless steel with normal carbon content is the maximum consistent with good refractory maintenance and economic recovery of chromium. In the case of the very low-carbon stainless steels, namely those having a carbon content of less than 0·03%, experience has shown it to be impractical in large furnaces to charge significant amounts of chromium-bearing scrap, because of the extreme difficulty in attaining the required carbon level. The development of commercial production of the very low-carbon steels in basic hearths came about through better understanding of the chemistry of the process and availability of ferrochromium of extremely low-carbon content.

Carbon and silicon contents for a charge vary widely depending on local conditions. Experience under some operating conditions has indicated that an increase in carbon content, for example, above 0·40%, may result in an increase in the time required for decarburization. The amount of silicon in the charge has generally been fixed by the amount contained in charge scrap and alloys. While some experimentation has been carried out with additions of silicon to the charge for the purpose of obtaining a rapid rise in temperature in the early stage of oxygen injection, knowledge of the overall benefits of this practice is limited. Practice in regard to the use of fluxes shows considerable variation. In some cases, part or all of the lime is added in the cold charge, whilst in others, these additions are postponed until the slag reduction period.

The condition of the steel bath prior to decarburization may vary widely. In some cases, the oxygen injection is started when the bath is only partially melted, whilst in others, a completely fluid bath is heated to a reasonably high temperature before starting the blow. Recently, there has been a trend toward faster injection and, in some large furnace operations, the rate of oxygen input has been increased to approximately 1000 cu. ft./hr. per net ton with a substantial reduction in the time of the decarburization period.

Silicon is the most widely used element for the reduction of metallics from the oxidized slag, and alloys of various concentrations of chromium, manganese, and silicon, as well as standard types of ferrosilicon, are available. Aluminium is favoured under some conditions and has been used effectively in complex chromium–silicon–aluminium alloys. However, silicon alloys generally provide a lower cost agent for oxide reduction than does aluminium. One slag reduction practice uses the silicon alloy in small size with the intention of reducing the slag directly. Another practice uses massive lumps of the alloy for the purpose of rapidly increasing the silicon content of the bath. Silicon usage has developed on the basis of experience, and the major restriction has been the maximum content of silicon specified in the steel. In cases where the silicon content of the bath after slag reduction is above that required, it has been common practice to use oxygen for silicon removal. Although the chromium concentration tends to become lower in slags of higher basicity, neutral slags are widely used to achieve the minimum chromium losses associated with lower slag volume, and to minimize a tendency toward excessive refractory attack. The addition of material, such as low-carbon ferrochromium and heavy croppings of cold scrap, is frequently used as a method of lowering bath temperature and of increasing the concentration of chromium.

Achievement of homogeneity in the metal and completion of reaction with the slag are facilitated by several methods of mechanical stirring. One practice is to agitate the bath with a large paddle attached to the charging machine. There has been renewed interest in the long-established practice of ' reladling ' after slag reduction. This procedure consists of tapping the heat into a ladle, pouring the slag from the lip of the ladle, and then returning the metal to the furnace. The practice has a number of obvious advantages. Refractories are cooled at the stage when continuance at the high temperature could cause serious deterioration, and during the reladling period minor refractory repairs may be made. Other advantages of the practice are rapid cooling of the metal and thorough mixing, with the result that samples taken after reladling closely represent the bath, and control of steel composition is improved. More complete recovery of chromium from the slag is obtained as the result of mixing slag and metal during the tapping operation. Induction stirring provides another method for control of bath uniformity.

Finishing slags of lime shaped with crushed silicon alloys have wide application. In some instances, low silica slags shaped up with aluminium are preferred in order to minimize reduction of silicon when additions of titanium are required. Deoxidation of stainless steels is carried out by manganese and silicon within the limits of the steel composition, and some supplementary deoxidizers such as aluminium, calcium alloys, and titanium have found wide application. Aluminium is frequently used in deoxidation of the plain chromium steels, and calcium alloys are commonly used in both plain chromium and nickel-bearing grades. These deoxidizing additions are made both in the furnace and in the ladle.

The following paper represents an extension of previously reported studies by the Electro Metallurgical Company on stainless steel melting practice. This programme has been designed to gain a better understanding of the process in order to resolve some of the questions evident in the above outline of current practices. Although the oxidizing phase of the process is fairly well understood, further study of the reducing reactions has been carried out. The chromium–carbon–temperature relation has been revised in the light of later work. The critical effect of initial temperature before starting the oxygen blow and the significance of the rate of oxygen injection have been explored to improve the control of oxidation. After

the carbon is oxidized to the desired level, the reduction of metallic oxides from the slag presents many problems in quantitative control. The well-known effects of slag basicity and residual silicon content, as well as the chromium content of the metal and the mechanical factor affecting approach to equilibrium, have been found to be the major variables of the reduction reaction. Although much more accurate studies of reduction are needed, it is evident that practices resulting in high chromium efficiency can be predicted. Finishing practices designed to control the levels of nitrogen, oxygen, and sulphur have also been studied. Residual oxygen prior to tapping has been found to be in large part dependent on the composition and temperature of the metal. Whilst a sufficient knowledge of the oxidizing and reducing practices has been gained to serve as a guide to economical production of stainless steel, additional study of the reactions and much more accurate empirical data are needed to predict and control optimum conditions for the melting of stainless steel.

OXIDATION OF CARBON AND METALLICS

The decarburization of chromium-bearing metal with oxygen revolutionized stainless steel melting practice. Although the possibilities were recognized by Bigge[1] in 1924, it was not until large quantities of oxygen became available that oxygen could be used effectively for chromium steel scrap utilization.[2] Oxygen promoted attainment of the high temperatures necessary to avoid excessive chromium oxidation, but it soon became apparent that a better understanding of the oxidation was essential to predict composition and temperature. The relations among carbon, chromium, and temperature were described by Hilty[3] in 1948 and were extended by Hilty, Healy, and Crafts[4] to provide a basis for estimating the amounts of chromium, manganese, and iron oxidized in the process of decarburization. This study has been continued and extended to evaluate the heat of oxidation and the heat losses of the furnace. Thus, if the composition and temperature of the melted metal and the rate of oxygen injection are known, it has become possible to predict, after blowing to a given carbon content, the temperature, chromium (manganese) content, and weight of metal oxidized. These calculations are at present insufficiently precise to be adequate for practical steelmaking, but they may serve as a basis for the relative evaluation of different practices.

Chromium–Carbon–Temperature Relation

The chromium–carbon–temperature relation originally developed by Hilty expressed the ratio of the chromium to the carbon content of a chromium steel bath after oxidation as a function of temperature, according to the equation:

$$\log \frac{\%\ \mathrm{Cr}}{\%\ \mathrm{C}} = -\frac{15200}{T} + 9{\cdot}46 \qquad \ldots\ldots(1)$$

where T is the absolute temperature.

Since this relation could not apply at very low carbon and chromium concentrations, Hilty, Healy, and Crafts postulated an extension into the low-concentration region by thermodynamic calculation based on the following reaction:

$$(FeCr_2O_4)(s) + 4\underline{C}^* = Fe + 2\underline{Cr}^* + 4CO(g) \qquad \ldots\ldots(2)$$

In this calculation the thermodynamic activity coefficients of chromium and carbon in the relatively dilute solution were assumed to be unity, so that at 1 atm. pressure of CO,

$$\tfrac{1}{2}\log K_2 = \log \frac{\%\ \mathrm{Cr}}{(\%\ \mathrm{C})^2} = -\frac{21250}{T} + 13{\cdot}88 \qquad \ldots(3)$$

Hilty, Healy, and Crafts then expressed the complete chromium–carbon–temperature relation as a set of intersecting curves defined by equations (1) and (3).

In evaluating his original experimental results, Hilty considered that the probable reaction was:

$$(CrO)(s) + \underline{C} = \underline{Cr} + CO(g) \qquad \ldots\ldots(4)$$

and that at 1 atm. pressure of CO, $K_4 = \%\ \mathrm{Cr}/\%\ \mathrm{C}$.

He based this consideration on the fact that reaction (4) and equation (1) fit the observations rather well without any complications regarding the thermodynamic activities of carbon and chromium beyond the assumption that they were equal to the concentrations. Hilty, Forgeng, and Folkman,[5] however, have recently demonstrated that three different oxide phases, chromite, distorted spinel, and Cr_3O_4, are involved in the reaction, depending on the concentration of chromium in the metal. Moreover, Richardson and Dennis[6] have shown that chromium has a substantial effect on the thermodynamic activity of carbon in molten Fe–Cr–C solutions. Consequently, although Hilty's original relation as stated by equation (1) has been found valid in or near the range of his experimental observations, its extrapolation to temperatures and compositions deviating significantly from this range is scarcely justified. Recognition of this situation has led to a re-evaluation of the chromium–carbon–temperature relation in the light of present knowledge.

In view of the results of Hilty, Forgeng, and Folkman the limiting equilibria of the decarburizing reaction are defined by the following equations in which the formula $Fe_{0{\cdot}67}Cr_{2{\cdot}33}O_4$ is considered to be the most likely representation of 'distorted spinel,' a denotes activity, and p signifies pressure.

* Underlining of symbols indicates that these elements are dissolved in the liquid metal phase and that their standard states are chosen at 1% concentrations in the solution.

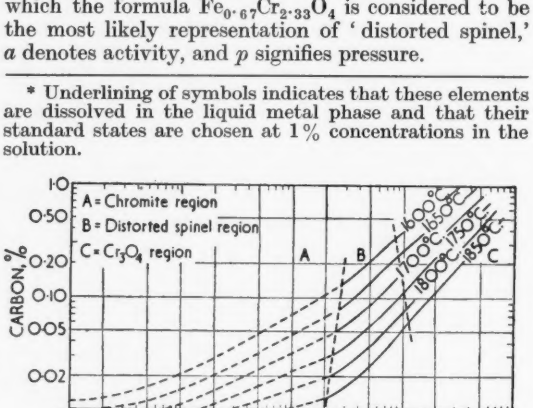

Fig. 1—Revised chromium–carbon–temperature diagram

Chromite range:

$$(FeCr_2O_4)(s) + 4\underline{C} = Fe + 2\underline{Cr} + 4CO(g) \quad ...(5)$$

$$K_5 = \frac{a_{Fe} \cdot a_{Cr}^2 \cdot p_{CO}^4}{a_C^4} \quad ...(6)$$

Distorted spinel range:

$$(Fe_{0\cdot67}Cr_{2\cdot33}O_4)(s) + 4\underline{C} = 0\cdot67Fe + 2\cdot33\underline{Cr} + 4CO(g) \quad ...(7)$$

$$K_7 = \frac{a_{Fe}^{0.67} \cdot a_{Cr}^{2.33} \cdot p_{CO}^4}{a_C^4} \quad ...(8)$$

Cr_3O_4 range:

$$(Cr_3O_4)(s) + 4\underline{C} = 3\underline{Cr} + 4CO(g) \quad ...(9)$$

$$K_9 = \frac{a_{Cr}^3 \cdot p_{CO}^4}{a_C^4} \quad ...(10)$$

By means of equations (6), (8), and (10), employing activity coefficients for carbon calculated from the data of Richardson and Dennis and utilizing the oxide phase boundaries established by Hilty, Forgeng, and Folkman, the revised chromium–carbon–temperature diagram shown in Fig. 1 has been derived from Hilty's original observations on the assumption that the CO pressure was substantially 1 atm. Since the curves in the chromite region, region *A* of the diagram, are established with less certainty, due to lack of direct observations, they are plotted as broken lines.

The equations for the respective oxide phase regions are as follows:

Chromite region (*A*):

$$4 \log \% C + \frac{1432}{T} \% C = 2 \log \% Cr + \left(\frac{7326}{T} - 3\cdot762\right) \% Cr + \log \frac{\% Fe}{100} + \frac{44250}{T} - 28\cdot32 \quad ...(11)$$

Distorted spinel region (*B*):

$$4 \log \% C + \frac{1432}{T} \% C = 2\cdot33 \log \% Cr + \left(\frac{160}{T} + 0\cdot057\right) \% Cr + 0\cdot667 \log \frac{\% Fe}{100} + \frac{60760}{T} - 37\cdot32 \quad ...(12)$$

Cr_3O_4 region (*C*):

$$4 \log \% C + \frac{1432}{T} \% C = 3 \log \% Cr + \left(\frac{160}{T} - 0\cdot0476\right) \% Cr + \frac{57100}{T} - 35\cdot16 \quad ...(13)$$

These equations, however, are cumbersome, and for practical application in chromium steel melting, simplification of them is desirable.

In the chromite region the iron content of the bath closely approaches 100% and the carbon content is usually quite low, so that the second and fifth terms of equation (11) are very small and can be ignored without introducing serious error. Up to about 3% of chromium, then, the relation can be expressed as

$$\log \frac{\% Cr}{(\% C)^2} = -\frac{22125}{T} - \left(\frac{3663}{T} - 1\cdot881\right) \% Cr + 14\cdot16 \quad ...(14)$$

Between 3 and 30% of chromium, as illustrated by Fig. 1, the relation approximates to linearity, so that for practical purposes it may be considered as such. Consequently, within the range of 3 to 30% of chromium and the temperatures of interest in steelmaking the relation can be expressed as a single, approximate equation as follows:

$$\log \frac{\% Cr}{\% C} = -\frac{13800}{T} + 8\cdot76 \quad ...(15)$$

It is notable that equation (15), whilst differing somewhat from equation (1), represents Hilty's original results equally as well as equation (1).

The derivation of the revised chromium–carbon–temperature diagram and equations (11), (12), and (13), carried out with the assistance of John Chipman of the Massachusetts Institute of Technology, will be described more fully by W. A. Krivsky and D. C. Hilty in a subsequent publication. The diagram and equations as reported in the present paper represent a preliminary summary of their results.

In practical steelmaking manganese is always present and must be considered in the above relation. As pointed out by Hilty, Healy, and Crafts, manganese may be assumed to be equivalent to chromium and the total of manganese plus chromium should be used for estimating temperature. Rassbach and Saunders[7] demonstrated that this relation was also valid for the calculation of metal oxidized during decarburization in the case of charges containing up to 10% of manganese. Such equivalency is of special interest in view of the recent development of chromium–manganese steels with relatively low nickel contents. These steels appear to be amenable to the same oxidation calculations as the plain chromium steels if the sum of the chromium and manganese is assumed to be equivalent to chromium.

Estimation of Metallic Oxidation

In order to determine the optimum initial charge, the rate and duration of the oxygen blow, and the amount of reducing agent for recovering metallic values from the slag, it is necessary to be able to estimate the extent of metallic oxidation during decarburization. A method for the determination of metallic oxidation, based on the empirical finding that the relative proportions of chromium plus manganese and iron in the slag bear a definite relation to the ratio of chromium plus manganese to iron in the metal, was demonstrated by Hilty, Healy, and Crafts on experimental 1-ton heats and confirmed by Rassbach and Saunders on commercial heats. The relation between chromium plus manganese divided by the iron in slag and metal is illustrated in Fig. 2. The following expression was derived for calculation of metal oxidation during decarburization:

$$W = 2000 \frac{(Cr_1 + Mn_1) - (Cr_2 + Mn_2)}{\frac{100\,S}{S+1} - (Cr_2 + Mn_2)} \quad ...(16)$$

where W is the pounds of chromium plus manganese plus iron oxidized per short ton of charge; Cr_1, the percentage of chromium in the initial charge; Mn_1, the percentage of manganese in the initial charge; Cr_2, the percentage of chromium in the metal after oxidation; Mn_2, the percentage of manganese in the

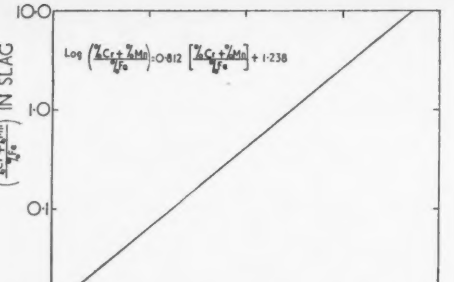

Fig. 2—Relation of chromium plus manganese to iron in slag and metal, according to Hilty, Healy, and Crafts

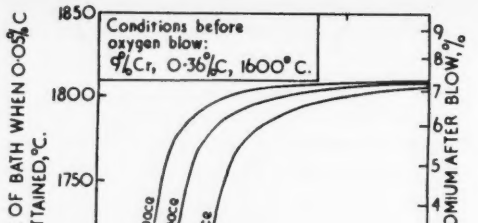

Fig. 4—Influence of oxygen input rate on temperature rise in furnaces of different sizes

metal after oxidation; and $S = (\%Cr + \%Mn)/\%$ Fe in the slag after oxidation.

The amount of metallic oxidation, W, in heats oxidized to any given carbon content at any specified temperature may be calculated by the use of Fig. 2 for estimating S, and the chromium–carbon–temperature relation given in Fig. 1 for charges containing the amount of chromium, manganese, and nickel used for making stainless steel. Typical charts for plain chromium steel charges after oxidation to 0·015% and 0·05% of carbon are shown in Figs. 3*a* and *b*. It should be noted that this relation is only applicable when the state of equilibrium expressed by Fig. 1 is attained. If nickel is present in the charge it should not be included as part of the iron content in the calculation.

In order to decarburize a charge containing a substantial amount of stainless steel scrap without excessive oxidation of chromium, it is essential that the heat resulting from oxidation of carbon, silicon, chromium, manganese, and iron exceed the radiation losses. These factors have been evaluated by G. W. Healy for the Linde Air Products Company in a study that has not yet been published. Typical conditions are illustrated in Figs. 4, 5, and 6. The evaluation was based on well-established heat balance relationships. It involved an analysis of the rate of heat loss and rate of heat input during the period from melt down to end of the oxygen blow for specific furnaces for which data were available. Heat inputs were calculated from the heats of oxidation of the elements oxidized and from such electrical power as may have been employed. Temperatures involved in calculation of the heat losses included a few immersion thermocouple measurements but were mainly estimated from the revised chromium–carbon–temperature diagram illustrated by Fig. 1. Analysis of the radiation loss component of the total heat losses indicated considerable difference between heats having highly liquid slags and those with slags containing a large proportion of solid phases. Radiation losses were significantly lower in the latter case. Moreover, the heat content of the solid slags is also lower so that less heat was lost by absorption. Figures 4, 5, and 6 are based on slags tending toward the solid side. If highly fluid slags were present, the curves in Fig. 4 would shift to lower temperature and higher rates of oxygen input, whilst those of Figs. 5 and 6 would shift toward higher oxidation losses and oxygen consumption.

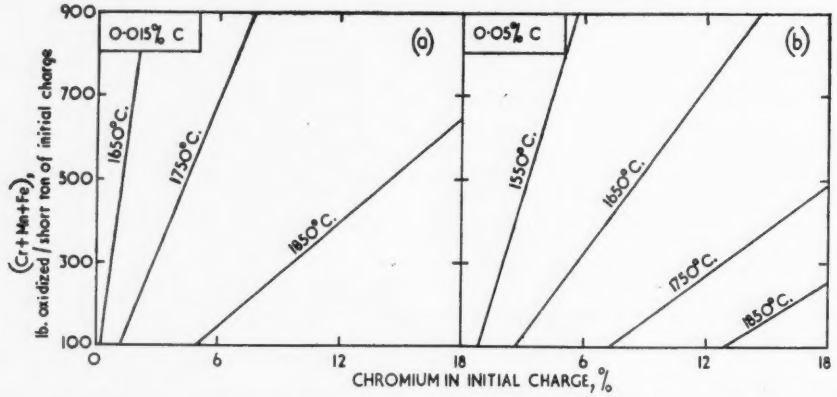

Fig. 3—Estimation of metal oxidized in blowing with oxygen to (*a*) 0·015%, (*b*) 0·05% of carbon

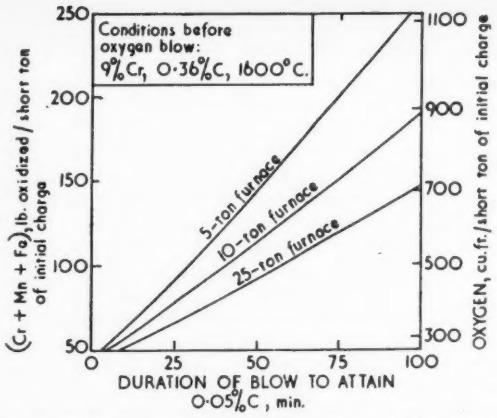
Conditions before oxygen blow: 9% Cr, 0·36% C, 1600° C.
5-ton furnace
10-ton furnace
25-ton furnace
(Cr + Mn + Fe), lb. oxidized / short ton of initial charge
OXYGEN, cu. ft. / short ton of initial charge
DURATION OF BLOW TO ATTAIN 0·05% C, min.

Fig. 5—Influence of oxygen input rate on duration of blow, oxygen consumption, and oxidation of the bath in furnaces of different sizes

Individual furnaces may be expected to vary somewhat from the indicated values since the rate of heat loss will depend not only on capacity, but also on other details of construction. Further, the examples are simplified by assuming a specific charge composition consisting only of carbon, chromium, and iron without manganese or silicon. The charts are, however, illustrative of the basic principles and confirm the advantages of the current trend toward higher rates of oxygen injection in economy of oxygen and reducing agents and also suggest the danger to refractories from high temperature and violent reactions.

The effects of rate of oxygen injection on temperature and associated chromium content after decarburization from an initial charge of 0·36% of carbon and 9·00% of chromium at 1600° C. to 0·05% of carbon are shown in Fig. 4. It is evident that the rate of oxygen input is quite critical. Below a certain rate depending on the size of the furnace, extra power is necessary to keep the bath molten. At very high rates there is a ceiling imposed on temperature by the

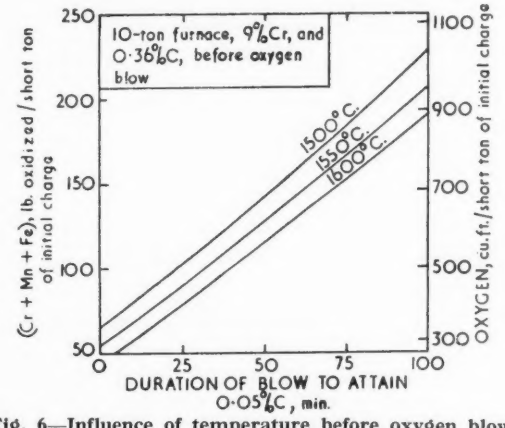
10-ton furnace, 9% Cr, and 0·36% C, before oxygen blow
1500° C.
1550° C.
1600° C.
(Cr + Mn + Fe), lb. oxidized / short ton of initial charge
OXYGEN, cu. ft. / short ton of initial charge
DURATION OF BLOW TO ATTAIN 0·05% C, min.

Fig. 6—Influence of temperature before oxygen blow on duration of blow, oxygen consumption, and oxidation of the bath

Table I

ERRORS RESULTING IN A 0·01% CHANGE IN FINAL CARBON

Metal containing nominally 9% Cr, 0·36% C at 1600° C. is blown with 4350 cu. ft. oxygen in 30 min. in a 10-ton furnace, aiming at 0·05% C

Initial carbon	**in error by**			**0·12%**
Initial chromium	,,	,,	,,	**1·4%**
Initial temperature	,,	,,	,,	**25° C.**
Heat loss rate	,,	,,	,,	**17%**
Oxygen volume	,,	,,	,,	**6%**

increased radiation losses. Minor changes at the intermediate rates of oxygen injection have a marked influence on temperature and chromium content. The same data are charted in Fig. 5 to indicate the effect of rate of oxygen injection in terms of the duration of oxygen blow required to reach the same end point—0·05% of carbon—on the oxygen usage and the associated oxidation of metallics. The shorter time (higher rate) of injection required for decarburization results in lower consumption of oxygen and less metallic oxidation. The effect of initial temperature is illustrated in Fig. 6.

The theoretical treatment of the oxidation process which led to the calculation of Figs. 4–6 also permits the estimation of the factors that influence the final carbon value when a given quantity of oxygen, estimated to result in 0·05% of carbon, is injected in a predetermined time. These are shown in Table I.

From a practical operating standpoint, it would appear that the initial temperature is likely to be the factor causing the most variability once time is standardized. It is also apparent that the errors may be additive, so that it is not surprising that frequently metal containing from 0·03 to 0·07% of carbon is made when 0·05% is the aim point.

The beneficial effect of extra fuel for oxidation, such as high initial carbon or silicon contents, is of primary value in raising the initial temperature. In practice it has seldom been found desirable to exceed 0·40% of carbon in the charge as the difficulties of furnace operation more than balance the heat of oxidation of the extra carbon. High silicon also is beneficial at the start of oxidation, but the resulting silica must be neutralized with lime or magnesia from the refractories.

By application of the relations described above, oxygen blowing practices suitable for given sets of practical operating conditions may be predicted. For example, consider the situation involving a 10-ton furnace in which it may not be desirable to exceed a temperature of approximately 1800° C. Assume that a source of oxygen capable of supplying 20,000 cu. ft. of oxygen per hour is available. It is desired to decarburize a charge containing approximately 9% of chromium plus manganese and 0·36% of carbon at meltdown to 0·05% of carbon. The problem is to decide at what rate and how long to blow oxygen into the bath, and to estimate the chromium and manganese contents of the bath, as well as the amount of metal that may be oxidized, for purposes of determining the quantity of slag reduction agents to be added.

Figure 4 indicates that for a 10-ton charge of the specified composition, if the bath is heated to 1600° C. prior to the start of the oxygen blow, the maximum permissible temperature will be attained with an oxygen input rate of approximately 10,300 cu. ft./hr., or about half the available supply. According to Fig. 1, the bath will contain approximately 6·8% of chromium plus manganese at the end of the oxygen blow. By means of Fig. 2 and equation (16), the amount of metallic oxidation is estimated to be 732 lb. Figure 5 then shows that a blowing period of 21 min. will be required resulting in oxygen consumption of 3600 cu. ft.

It may be noted that similar results with regard to metallic oxidation and a temperature of 1800° C. at the end of the oxygen blow may not be achieved if the oxygen blow is started as soon as the bath is molten without a rate of oxygen input far greater than the 20,000 cu. ft./hr. that is available. According to Fig. 6, a temperature of 1500° C. at the start of decarburization would require 6 min. of oxygen blow at a blowing rate of 36,000 cu. ft./hr. for the same results. Similar applications of these principles to other aspects of oxidation problems will be evident.

REDUCTION OF METAL OXIDES FROM SLAG

Reduction of metallic oxides from the slag after completion of decarburization is an essential economy in the utilization of stainless steel scrap. At the end of oxidation the slag contains a large amount of the chromium, manganese, and iron representing up to a third of the initial charge. These metallic values are usually recovered by reduction with silicon in the form of alloys containing various amounts of iron and chromium. Aluminium is sometimes used as a supplementary agent. The role of lime in neutralizing the silica has long been recognized as essential to efficient stripping of the slag. Its corollary, the relatively low recoveries that are attained in chromite- and acid-lined furnaces,[8, 9] has dictated the use of basic-lined furnaces for maximum chromium yields. Although chromium recoveries in excess of 95% may be realized from silicon reduction under basic slags, the chemical and mechanical factors affecting the reaction have so many areas of uncertainty that optimum conditions have been difficult to define.

Chemistry of Slag Reduction

While the chromium content of slags is usually expressed as Cr_2O_3, Hilty, Forgeng, and Folkman indicated that the oxide phase stable at the temperatures and bath compositions of practical interest with regard to slag reduction is Cr_3O_4, or more properly, $Fe_xCr_{(3-x)}O_4$. Therefore, the reduction reaction may be written

$$(Cr_3O_4) + 2\underline{Si} = 3\underline{Cr} + 2(SiO_2) \quad \ldots\ldots\ldots\ldots (17)$$

This reaction is illustrated by Fig. 7 which shows the relation between chromium and silicon in iron alloys saturated with silica as well as chromium oxide. Figure 7 was derived from a laboratory investigation of iron–chromium alloys which were melted in silica crucibles and permitted to reduce silicon from the crucibles. In basic furnaces this reaction is driven toward completion by increasing the silicon content of the metal and by neutralizing the resulting silica with lime. The relation with lime/silica ratio and silicon content was demonstrated by Taylor.[10] It was later indicated by Crafts and Rassbach[11] that magnesia was equivalent to lime and should be included in the basicity relation. Subsequent study of additional data has tended to confirm that magnesia is about as effective as lime in neutralizing silica. This relation at 0·3–1·0% of silicon between basicity and metal retained in the slag as oxide is shown, in Figs. 8*a* and *b*, as modified by Rassbach and Saunders. It should be noted that the degree of error in this relation is very high with respect to both silicon content and basicity. Statistical study of the available data has eliminated from significant interest factors such as alumina in the slag after reduction, carbon content of the metal, composition of the slag and temperature of the metal at the end of the oxidizing period, but has confirmed the significance of basicity (including magnesia), silicon and chromium contents of the metal, and factors of practice tending to accelerate approach to equilibrium.

The degree of approach to equilibrium is particularly difficult to evaluate as the equilibrium conditions have not been determined and because the data, more obviously above a basicity ratio of 1:4, tend to

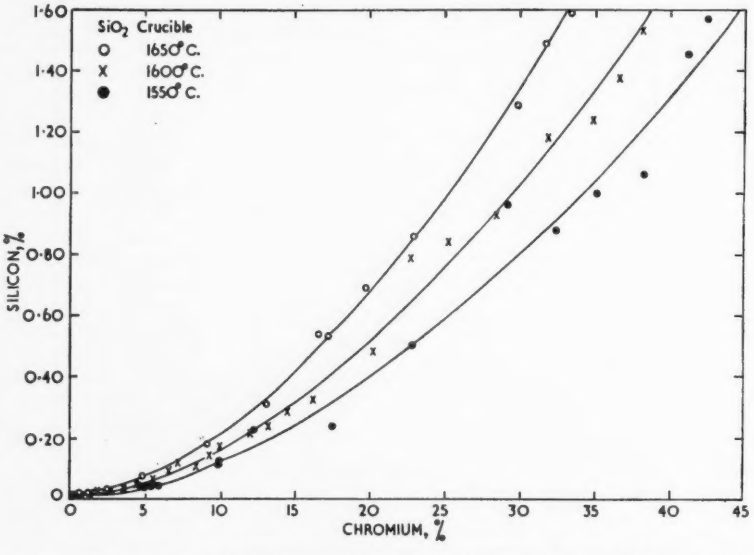

Fig. 7—Chromium and silicon contents of Fe–Cr–Si alloys in the presence of both chromium oxide and silica

fall into two groups. As pointed out by Rassbach and Saunders, in larger furnaces the metallic oxides in high-basicity slags were significantly higher, as indicated by the broken lines in Fig. 8, than in the slags of the 1-ton experimental furnace. They ascribe this to stratification and imperfect slag–metal reaction. This was confirmed by Merrill and St. Vincent[12] for ferrochromium and by Texter[13] for stainless steel. Texter tapped the metal into a ladle and poured it back into the furnace to promote thorough mixing. As shown in Fig. 9, the reaction proceeded toward a significantly lower chromium oxide content in the slag.

The mechanical factor that slows the reaction has greatly increased the difficulties of evaluating the chemical factors entering into the reduction reaction. Further, no means have been found for isolating the mechanical factor because no criterion of equilibrium has been available. However, in addition to data previously reported, new data from a group of experimental 5-ton heats made by E. R. Saunders and W. L. Harbrecht were at hand. All of the data that were pertinent, data from a total of 64 heats, were analysed statistically by R. H. Gillespie without attempting to separate the mechanical factor. This analysis indicated that three factors, basicity, silicon content of the metal, and chromium content of the metal, were of primary significance. A theoretical consideration of these factors was then utilized to approximate their relative significance.

The equilibrium constant for the reduction reaction, reaction (17), is

$$K_{17} = \frac{a^3\mathrm{Cr}.a^2\mathrm{SiO_2}}{a^2\mathrm{Si}.a\mathrm{Cr_3O_4}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(18)$$

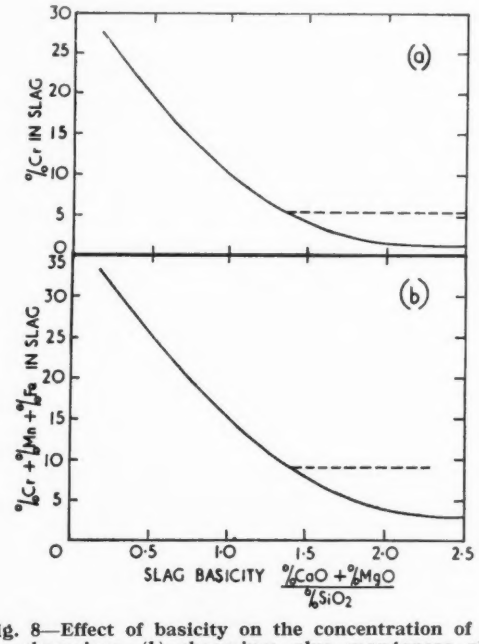

Fig. 8—Effect of basicity on the concentration of (*a*) chromium, (*b*) chromium plus manganese plus iron, in reduced slags, according to Rassbach and Saunders

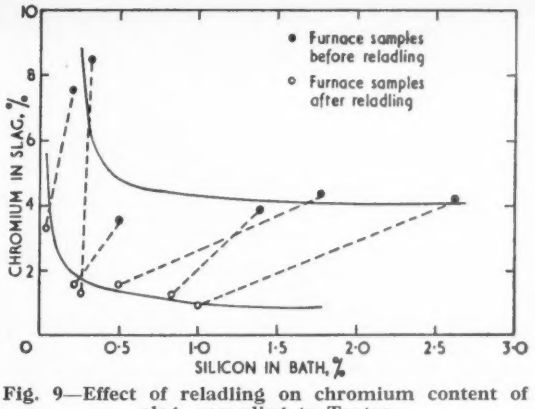

Fig. 9—Effect of reladling on chromium content of slag, according to Texter

From Fig. 7, however, the relation between chromium and silicon at chromium concentrations above 10% can be expressed as

$$K'_{17} = \frac{[\%\ \mathrm{Cr}]^3.a^2\mathrm{SiO_2}}{[\%\ \mathrm{Si}]^{1.75}.a\mathrm{Cr_3O_4}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(19)$$

From the studies of Rey,[14] as well as those of Darken and Gurry,[15] the following rough approximation of the average variation of the activity of SiO_2 with slag basicity over the range of basicities of interest here can be made:

$$a\mathrm{SiO_2} \propto (1/V)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots(20)$$

where

$$V = \frac{\%\ \mathrm{CaO} + \%\ \mathrm{MgO}}{\mathrm{SiO_2}}$$

By considering chromium concentration in the slag as a parameter of the activity of Cr_3O_4 and combining equations (19) and (20), the following relation is obtained:

$$\%\ \mathrm{Cr\ in\ slag} \propto \frac{[\%\ \mathrm{Cr}]^3}{[\%\ \mathrm{Si}]^{1.75}V^4} \quad \ldots\ldots\ldots\ldots(21)$$

Iron and manganese in the slag are considered to substitute directly for Cr in Cr_3O_4, so that they may be included in the relation as follows:

$$(\%\ \mathrm{Cr} + \%\ \mathrm{Mn} + \%\ \mathrm{Fe})\ \mathrm{in\ slag} \propto \frac{[\%\ \mathrm{Cr}]^3}{[\%\ \mathrm{Si}]^{1.75}V^4} \quad \ldots\ldots(22)$$

Equations (21) and (22) indicate that of the composition variables involved, basicity is most important in controlling the concentration of metallics remaining in the slag after reduction, with chromium content of the bath running a close second. Silicon content of the bath, however, is suggested to be only about one-half as effective as either of the others. It is notable that the statistical analysis mentioned above indicated the relative significance of these variables to be almost identical with that predicted by equations (21) and (22).

Data for the end of the slag reduction period from 15 experimental 1-ton heats, 37 experimental 5-ton heats, and 5 commercial heats ranging from 15 to 25 short tons in size were employed to evaluate equations (21) and (22), as shown in Figs. 10 and 11. The evident grouping of the 1-ton heats and the commercial heats on opposite sides of the data band, with the 5-ton heats distributed throughout the range, is considered highly significant. It is believed to be a reflection of

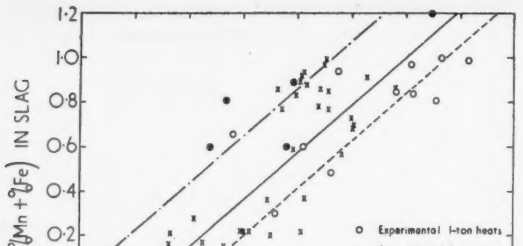

Fig. 10—Relations among bath composition, slag basicity, and chromium content of reduced slag

the effect of temperature. Although reliable measurements of temperature were not available, it is known that, whilst considerable temperature variation occurred in each group, the 1-ton heats as a class averaged in the order of 150° C. higher in temperature than the commercial heats and the 5-ton heats covered a wide range of temperature. Presumably, higher temperatures resulted in increased slag fluidity, activity, and homogeneity that greatly accelerated the reduction reaction.

The rate of the reduction reaction at the lower temperatures in the larger commercial furnaces is slowed by the concentration gradient of chromium in the metal. This stratification results in a higher chromium content near the slag/metal interface, which tends to oppose the reaction, so that it cannot be completed in a reasonable time in the larger and colder heats. By active stirring these concentration gradients can be minimized and the reaction completed as illustrated by Texter. Thus, the greater homogeneity of the bath and improved contact with the slag necessary to complete the reduction reaction may be realized by higher temperature and mechanical agitation. In this sense, the effect of mechanical agitation is in the same direction as that of temperature, and heats effectively agitated by stirring or reladling would be expected to retain less chromium in the slag for any given bath composition.

Prediction of Metal Recovery

In addition to the above relation, the efficiency of the silicon added for reduction must be known in order to predict chromium and silicon content of the metal as well as chromium recovery. Estimation of the silicon efficiency requires accurate data on slag composition and weight prior to reduction. Because of a tendency toward segregation, slag analyses are not reliable with respect to lime and silica, and accurate data on initial charge and additions must be utilized. Crafts and Rassbach found an average of $3 \cdot 0 \pm 0 \cdot 5$ lb. of chromium plus manganese plus iron reduced per pound of silicon. Rassbach and Saunders studied four commercial heats and reported a figure of $2 \cdot 55 \pm 0 \cdot 20$ lb. of metal per pound of silicon. The theoretical efficiency is approximately $2 \cdot 85$ lb. of metal per pound of silicon and some silicon is lost to the atmosphere. It is considered probable that a reliable figure for calculation lies somewhat above $2 \cdot 5$ lb. of metal reduced per pound of silicon, but this coefficient cannot be considered to be well established. The degree of the error, however, is probably no greater than is involved in the other factors included in the calculation. It is therefore considered that the method described by Hilty[11] can be utilized for the purpose of evaluating specific conditions in predicting an optimum practice. Such calculations indicate that practices for maximum chromium recovery should incorporate low slag volumes and slags of high basicity.

Other considerations may be more important than maximum chromium recovery in overall cost. For example, carbon pick-up under slags with a basicity factor greater than $1 \cdot 5$, is critical in very low-carbon steels. On the other hand, refractory corrosion, sulphur removal, etc., may dictate the use of more basic slags. High-manganese scrap utilization presents a special case in which high basicity approaching $2 \cdot 5$ is necessary to recover manganese values.[7] As the use of these very high basicity slags has many disadvantages, it would appear that high-manganese stainless steel scrap can be utilized most effectively as a cooling addition after oxidation so that the contained manganese is not lost even when the slag is not exceedingly basic. For steels that are sensitive to hydrogen absorption and under circumstances when dry lime is not available, a less reducing and therefore more acid slag may outweigh all considerations of chromium recovery.

NITROGEN, SULPHUR, AND OXYGEN IN THE FINISHING PERIOD

In the finishing period of the heat between slag reduction and tapping, the practical objectives are well defined, but much remains to be learned in regard to the reactions occurring in this phase of the process. In practical terms, the initial goal of the operator is to establish a low-oxide slag in order to avoid reoxidation and to lower sulphur. This slag

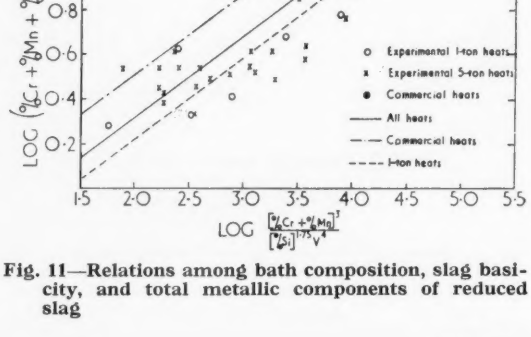

Fig. 11—Relations among bath composition, slag basicity, and total metallic components of reduced slag

provides a stable condition for maintaining close control of steel composition during the period when final alloy additions are made and the temperature of the bath is adjusted.

Single-slag practice involves carrying through to the end of the heat a substantial part or all of the partially reduced slag from the oxidizing period. In small-furnace practice time cycles are short and metallic oxidation is low, and the single-slag practice is used to good effect. Two-slag practice involves fairly complete removal of the partially reduced slag and shaping a new lime slag with fluorspar, sand, crushed ferrosilicon, aluminium, calcium–silicon, etc. The two-slag practice has wide application for steels in which close control of analysis and cleanliness are critical. Where electrical equipment does not provide close control of electrode movement, a single-slag or partial slag removal practice is preferable to avoid carbon contamination from the electrodes.

The residual elements, nitrogen, sulphur, and oxygen are affected by the steelmaking practice and require special consideration. Although sulphur and nitrogen are sometimes added intentionally for their specific alloying effects, in most cases they are present only as residuals. The inclusion content of steel has been associated with the oxygen content of the metal prior to final deoxidation; therefore the behaviour of oxygen in the process is of major interest.

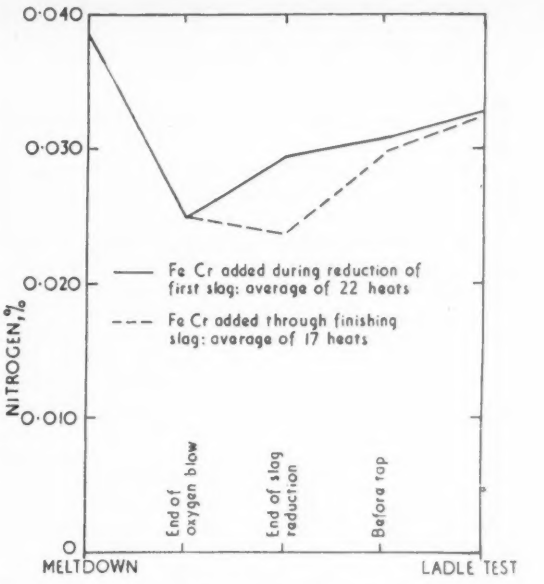

Fig. 12—Average nitrogen content at various stages of experimental 5-ton heats of 16·5% chromium steel

Nitrogen

A study of the behaviour of nitrogen in high-chromium steels may be separated into two broad classifications, namely, steels to which nitrogen is not added as a specified element and those to which intentional additions of nitrogen are made. Nitrogen is known to be a strong austenite former and its use is well established in chromium stainless steels for grain refinement, improved hardness, and greater strength and ductility at elevated temperatures. Nitrogen in the chromium–manganese austenitic steels presently under development by the industry is of primary importance in improving the hot-working properties, microstructural stability, and corrosion resistance.

Because of the increased interest and need for nitrogen as an alloying constituent in stainless steel, the subject has been investigated recently by Rassbach, Saunders, and Harbrecht.[16] Their investigation included a study of residual nitrogen and the recovery of nitrogen as a function of both the nitrogen concentration in the addition agent and the amount added in proportion to the solubility limit of the nitrogen in the steel bath. With regard to residual nitrogen, Rassbach, Saunders, and Harbrecht, and Henke and Carney in the discussion,[16] showed that in stainless steel heats the nitrogen content at melt is relatively high and is lowered during the oxygen blow to levels that are primarily dependent on the chromium content and the duration of the oxygen blow. While no strong correlation was found between chromium and nitrogen in the bath after oxidation, it was noted that heats having more than 5% of chromium in the bath had nitrogen contents generally in the range 0·02–0·03% compared to a range of 0·007% to 0·015% for baths containing 3% or less chromium. These investigators also demonstrated that during the finishing period of the heats residual nitrogen increased from the minimum level attained at the end of oxidation to a final level of about 0·03–0·04% regardless of the initial nitrogen content of the bath or the type of alloying additions employed. They suggested that this level is established by the furnace atmosphere. They also showed that melts with charges containing about 9–11% of chromium, 2–8% of manganese, 1–5% of nickel, and 0·07–0·08% of nitrogen, contained nitrogen in the range 0·055–0·085% at melt. During decarburization nitrogen was lowered to a range of 0·035 to 0·049%, which is significantly higher than in the plain chromium steels.

Observations of nitrogen content at various stages in the melting of 39 experimental 5-ton heats containing from 7 to 15% of chromium at meltdown have confirmed the results described by Rassbach, Saunders, and Harbrecht. In addition, as shown in Fig. 12, differences in the rate of nitrogen pick-up following the oxygen blow depended on whether the alloying additions were made during slag reduction or through the finishing slag later in the heats. The diagram clearly demonstrates, however, that approximately the same level of final nitrogen content was attained regardless of the alloying practice. Moreover, it is particularly noteworthy that in the melting of the experimental 5-ton heats, large and small additions of both conventional low-carbon ferrochromium as well as vacuum-decarburized ferrochromium alloy were employed with no significant differences on the behaviour of nitrogen. Rassbach, Saunders, and Harbrecht also described heats with virgin charges which at melt contained nitrogen in the range normal for arc-melted plain carbon steels. These heats also increased in nitrogen content during the

alloying and finishing period, so that the final nitrogen content was about the same as illustrated by Fig. 12 for heats made with chromium in the charge. In melting low-nitrogen stainless steels, therefore, it appears that the final nitrogen content is independent of the amount of scrap charged or the ferrochromium added.

In making the high-nitrogen steels, close control of final nitrogen content requires knowledge of recovery of nitrogen from the addition agent employed. Regularly used alloys for this purpose are nitrogen-bearing ferrochromium alloys varying in nitrogen content from 0·7 to 7·0% and electrolytic manganese nitrided to 5·5–7·0%. Lower recoveries result from increasing concentration of nitrogen in the ferro-alloy, and the efficiency of nitrogen additions to molten steel decreases as the saturation of the bath is approached. The solubility of nitrogen in molten iron–chromium alloys is increased by manganese as is the ability of these alloys to retain nitrogen upon solidification. Increased nitrogen content has proved to be of considerable value in improving the structural stability and the hot workability of high-manganese stainless steels.

Sulphur

Sulphur, except for intentional additions to improve machinability, is usually considered to be undesirable in stainless steel, and an effort is made to lower the sulphur content. High sulphur is generally believed to impair hot-working properties, especially in the nickel-bearing grades. It has long been recognized that sulphur removal is facilitated by basic slags, and this was demonstrated for stainless steel by Taylor. The influence of silicon was recognized by Schulz,[17] who noted that the sulphur content of stainless steels was reduced much more effectively than in low-alloy steels containing very little silicon. It has also been observed that desulphurization is accomplished readily under a lime–alumina slag when the metal contains an appreciable amount of aluminium.

The typical progress of desulphurization at various stages is shown by the data from 44 experimental 5-ton basic heats listed in Table II. These heats had 7–15% of chromium in the charge and were decarburized with oxygen. After partial reduction of the oxidized slags with silicon, new lime slags were shaped with crushed ferrosilicon. The finished steel contained about 16·5% of chromium, 0·08% of carbon, and 0·04% of silicon.

The experimental results showed little change in the sulphur content of the metal in the oxidizing period

Table II
PROGRESS OF DESULPHURIZATION

Period of Heat	Sulphur Content, %		
	Low	High	Average
At melt	0·021	0·039	0·031
After oxygen blow	0·021	0·044	0·031
End of reduction	0·015	0·034	0·023
Pre-tap	0·011	0·026	0·016
Tapped metal	0·008	0·022	0·012

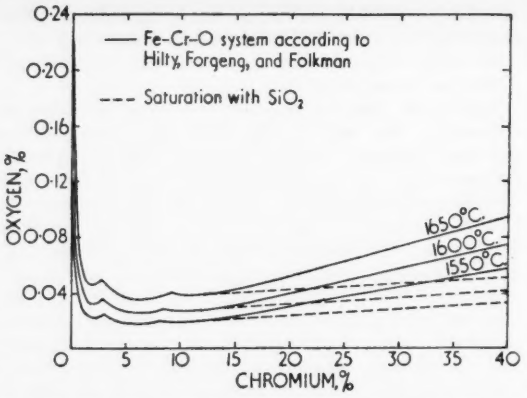

Fig. 13—Effect of silica saturation on the solubility of oxygen in molten iron–chromium alloys

of the melt. The reducing and finishing slags were relatively high in basicity and the residual silicon content of the bath after reduction was above 0·10%. Significant desulphurization took place during slag reduction and continued in the finishing period and tapping operation. Within the scope of the data from these heats, the final sulphur content showed no correlation with silicon content after reduction, slag V-ratio, or tapping temperature. With the raw materials used in these heats, the sulphur content of the bath at melt ranged from 0·021 to 0·039% and only two heats of 44 had final sulphur above 0·015%. This is cited as an indication of the ease with which sulphur is removed from melts made with regularly available materials.

Queneau and Klimas[18] found it helpful to utilize two finishing slags to reach very low sulphur levels, when high-sulphur scrap or steel turnings contaminated with sulphur compounds are charged. In melting the very low-carbon steels the finishing slags are frequently less basic and higher in metallic oxides than those in stainless steels of normal carbon content. It has been observed that in these steels desulphurization is promoted with a high residual silicon content in the neighbourhood of 1% during the finishing period. Drop in sulphur content in the tapping process due to improved slag–metal reaction is fairly consistent and is relied upon in commercial practice.

Oxygen

Although understanding of the specific effects of oxygen in stainless steels is limited, it is well recognized that oxygen plays a vital role in establishing the quality of the finished product. There is considerable evidence that oxygen may adversely affect the workability and mechanical properties of the steel. Customarily, however, the steelmaker defines steel quality in terms of cleanliness or relative freedom from non-metallic inclusions and considers oxygen from that viewpoint.

The types, sizes, and distribution of non-metallic inclusions are influenced by a number of factors, particularly the kind and sequence of deoxidation employed and the freezing rate of the metal. The total

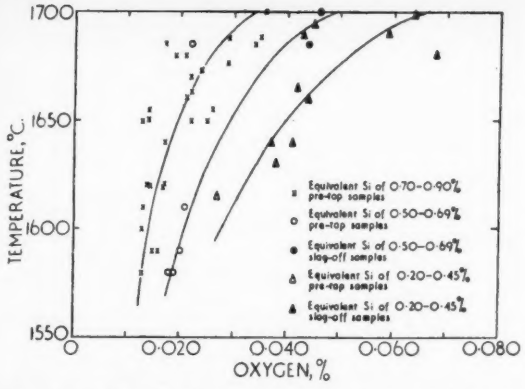

Fig. 14—Influence of temperature and composition on the oxygen content of the bath in experimental 5-ton heats of 16·5% chromium steel

quantity of non-metallic matter, excluding mechanically entrained slag or refractory enclosures, however, is to a considerable extent a function of the oxygen content of the heat. The minimum amount of non-metallics, therefore, is limited by the equilibrium oxygen content for the specific metal composition. Consequently, the problem of oxygen control may be examined with respect to degree of approach to equilibrium.

The solubility of oxygen in the fundamental Fe–Cr–O system has been studied by Wentrup and Knapp,[19] Chen and Chipman,[20] Linchevskij and Samarin,[21] Turkdogan,[22] and most recently by Hilty, Forgeng, and Folkman. Oxygen solubility drops to a minimum in the range of 5 to 10% of chromium and then increases as illustrated by the solid lines in Fig. 13, according to Hilty, Forgeng, and Folkman. Moreover, as also indicated by Fig. 13, oxygen solubility increases rather substantially with increasing temperature.

Since chromium steels contain significant amounts of other elements that limit oxygen solubility, information regarding the modification of the Fe–Cr–O system by these elements is more pertinent, but data are mostly lacking. The most common of these deoxidizers, however, is silicon, and an indication of the effect of silicon may be obtained from preliminary results of a study of oxygen solubility in Fe–Cr–O alloys melted in a silica crucible, i.e. in the presence of SiO_2 saturation, shown as broken lines in Fig. 13. Silicon contents corresponding to specific chromium and oxygen contents on these curves may be determined by reference to Fig. 7. For example, at equilibrium at 1650° C. a melt of 18% of chromium containing just enough silicon to produce saturation of the slag with SiO_2 would have silicon and oxygen contents of 0·57% and 0·041%, respectively, whilst at 1550° C., a melt of 18% of chromium at silica saturation would contain only 0·33% of silicon and 0·022% of oxygen. It is apparent that, within the composition range of interest in melting stainless steels, silicon lowers the solubility of oxygen. The relative deoxidizing power of silicon, however, is reduced by increasing chromium concentration.

Vacuum-fusion oxygen determinations and corresponding temperature observations were available for thirty-three 5-ton heats of 16·5% chromium steel. These heats were made by different practices with regard to amount of chromium in the initial charge and to whether the required ferrochromium addition was made during slag reduction or through the second slag during the finishing period. Both regular and vacuum-decarburized ferrochromium were used in these tests. Regardless of practice, however, the analytical samples all represented the same approximate level of chromium content (16·5%) and were taken either just before tap (pre-tap) or at the end of the slag reduction period (slag-off). Bath temperatures were measured by conventional immersion thermocouples.

Since all of the samples contained various amounts of silicon and manganese, evaluation of the oxygen results involved some estimate of the influence of manganese. In the absence of data regarding the effect of manganese on the solubility of oxygen in iron–chromium alloys containing silicon, an approximation of the effect was derived by interpolation from the results of Hilty and Crafts[23] on the solubility of oxygen in liquid iron containing silicon and manganese. It was assumed that the relative effects of silicon and manganese in iron–chromium alloys might be similar to their effects in iron. The silicon and manganese contents of the samples were then expressed as 'equivalent silicon' contents, meaning the silicon contents required to produce the same degree of deoxidation in the absence of manganese.

The oxygen contents were then grouped in ranges of 'equivalent silicon' contents and plotted against temperature, as illustrated by Fig. 14. The results clearly indicate that within the precision of the observations the oxygen contents of the heats depended only on temperature and composition. The oxygen contents of stainless steel heats, therefore, are inferred to be controlled principally by the equilibria establishing the limiting oxygen solubility. Thus, the specific amount, character, and time of the alloy additions are not critical with respect to the oxygen content, except as they affect temperature and composition. From this it would appear that lower oxygen contents are favoured by approach to the maximum specified manganese and silicon contents and by finishing at temperatures as low as may be consistent with good steelmaking practice. It is apparent that control of the optimum temperature is critical and that although high temperature leads to high oxygen contents, low temperature may also cause excessive contamination of the finished steel with inclusions or otherwise unsatisfactory ingots as a result of poor pouring conditions.

SUMMARY

Stainless steel melting practice has been investigated further in an effort to understand the chemical reactions sufficiently well that the empirical data can be utilized to predict and control the process. Although there is much to learn about the underlying principles and much more extensive and accurate data are needed, considerable progress has been made toward a rational basis for the design of economical practices.

In the study of the decarburizing reactions a further refinement of the chromium–carbon–temperature relation and an evaluation of the heat balance during the oxygen blow have been made. With these relations and the ratios between the concentrations of chromium and manganese with iron in the slag and metal, it is possible to predict the compositions and weights of metal and metallic oxides in the slag at the end of decarburization, if the composition and weight of the initial charge, the temperature when the oxygen blow is started, and the rate and duration of oxygen blow are known. The degree of precision of this calculation is considered to be hardly adequate for control purposes, but the calculation is believed to be useful for estimation of optimum practices. It has shown clearly the benefits to be derived from relatively high rates of oxygen input.

Understanding of the reducing reactions has been extended by a theoretical rationalization of a multiple correlation of the empirical data. The relations among basicity, silicon content, chromium content, and metallic oxides in the slag, as well as the mechanical and thermal factors affecting the rate of the reaction have been evaluated. The stoichiometric efficiency of silicon in the reduction is known well enough to permit calculation and prediction of the recovery of chromium. By combining the decarburizing and reducing stages of the process, it is feasible to determine the relative economy of comparative stainless-steel scrap melting practices.

The control of sulphur, nitrogen, and oxygen has been studied. Sulphur is readily lowered in silicon-bearing metal under a basic slag to relatively low levels. Residual nitrogen varies with the furnace conditions, but in the finished steel is more or less proportional to the chromium content. The oxygen content prior to tapping has been found to depend on composition and temperature regardless of the means by which additions of chromium are made. Minimum oxygen contents result from the lowest temperature consistent with good steelmaking practice and the highest manganese and silicon contents consistent with specified analysis. Thus, it would appear that the quality of the steel, as indicated by nitrogen, sulphur, and oxygen residuals, need not be affected by alloying practices designed to achieve the ultimate economy in chromium utilization.

References

1. H. C. Bigge: U.S. Patent 1,512,735.
2. J. H. Eisaman: *Steel*, 1948, vol. 123, 16th Aug., pp. 112–121.
3. D. C. Hilty: *Amer. Inst. Min. Met. Eng., Proc. Elec. Furn. Steel Conf.*, 1948, vol. 6, pp. 140–148; *Trans. Amer. Inst. Min. Met. Eng.*, 1949, vol. 185, pp. 91–95; *J. Met.*, 1949, vol. 1, Feb.
4. D. C. Hilty, G. W. Healy, and W. Crafts: *Trans. Amer. Inst. Min. Met. Eng.*, 1953, vol. 197, pp. 649–653; *J. Met.*, 1953, vol. 5, May.
5. D. C. Hilty, W. D. Forgeng, and R. L. Folkman: *Trans. Amer. Inst. Min. Met. Eng.*, 1955, vol. 203, pp. 253–268; *J. Met.*, 1955, vol. 7, Feb.
6. F. D. Richardson and W. E. Dennis: *J. Iron Steel Inst.*, 1953, vol. 175, pp. 257–263.
7. H. P. Rassbach and E. R. Saunders: *Trans. Amer. Inst. Min. Met. Eng.*, 1953, vol. 197, pp. 1009–1016; *J. Met.*, 1953, vol. 5, Aug.
8. J. E. Harrod: *Amer. Inst. Min. Met. Eng., Proc. Elec. Furn. Steel Conf.*, 1951, vol. 9, pp. 91–92.
9. D. C. Hilty: *Ibid.*, 1949, vol. 7, pp. 246–251.
10. C. R. Taylor: *Ibid.*, 1950, vol. 8, pp. 91–97.
11. W. Crafts and H. P. Rassbach: *Ibid.*, 1951, vol. 9, pp. 95–110.
12. T. W. Merrill and F. St. Vincent: *Ibid.*, 1953, vol. 11, pp. 69–73.
13. A. J. Texter: *Ibid.*, 1953, vol. 11, pp. 73–77.
14. M. Rey: *Disc. Faraday Soc.*, 1948, No. 4, pp. 257–265.
15. L. S. Darken and R. W. Gurry: "Physical Chemistry of Metals," pp. 340–341: 1953, New York, McGraw-Hill Book Co.
16. H. P. Rassbach, E. R. Saunders, and W. L. Harbrecht: *Amer. Inst. Min. Met. Eng., Proc. Elec. Furn. Steel Conf.*, 1953, vol. 11, pp. 244–263.
17. H. B. Schulz: *Ibid.*, 1944, vol. 2, pp. 123–124.
18. B. R. Queneau and C. V. Klimas: *Ibid.*, 1953, vol. 11, pp. 281–289.
19. H. Wentrup and B. Knapp: *Tech. Mitt. Krupp*, 1941, vol. 4, No. 11, pp. 237–256.
20. H. M. Chen and J. Chipman: *Trans. Amer. Soc. Metals*, 1947, vol. 38, pp. 70–113.
21. B. V. Linchevskij and A. M. Samarin: *Izvest. Akad. Nauk S.S.S.R., Otdelenie Tekn. Nauk*, 1953, No. 5, pp. 691–704.
22. E. T. Turkdogan: *J. Iron Steel Inst.*, 1954, vol. 178, pp. 278–283.
23. D. C. Hilty and W. Crafts: *Trans. Amer. Inst. Min. Met. Eng.*, 1950, vol. 188, pp. 425–436; *J. Met.*, 1950, vol. 2, Feb.

Removal of Sulphur during Iron-Ore Sintering

Part I—LABORATORY STUDIES OF THE KINETICS OF SULPHIDE AND SULPHATE DECOMPOSITION

By V. Giedroyc, Ph.D., D.I.C.

SYNOPSIS

Laboratory studies of the mechanism by which pyritic and sulphate sulphur is eliminated during sintering iron ores and of factors affecting the rate of sulphur removal were carried out using synthetic sinter mixes. Pyritic sulphur is oxidized to sulphur dioxide, part of which is removed with the waste gases, the remainder being absorbed by lime in the sinter mix, with the formation of calcium sulphate. The removal of sulphate sulphur takes place mainly by thermal decomposition at the reduced oxygen pressure resulting from the presence of incandescent carbon, and by reaction of calcium sulphate with silica and ferric oxide. For a given set of sintering conditions there is an optimum carbon content at which the rate of sulphur evolution is a maximum. 1142

IN ADDITION TO AGGLOMERATING ore fines, the sintering process may bring about beneficiation of the ore and adjustment of its chemical and mineralogical composition. In particular sintering offers a partial solution to the ever-growing problem of the removal of sulphur from the raw materials of iron-making.

In iron ores sulphur is present in two forms: sulphide and sulphate. The most common sulphur minerals are pyrites, gypsum, anhydrite, and, to a lesser extent, barytes. Moreover, additional sulphur is introduced into a sinter mix with the coke. The latter may contain sulphide, sulphate, and organic sulphur. Organic and pyritic sulphur behave similarly on ignition in air, producing sulphur dioxide, whereas under these conditions calcium and barium sulphates do not lose sulphur appreciably, even at high temperatures. Therefore when considering the removal of sulphur during sintering it is necessary to investigate the reactions of both pyritic and sulphate sulphur.

THEORETICAL CONSIDERATIONS

REACTIONS OF PYRITES

The reactions of pyrites have been extensively investigated. The kinetics of its thermal decomposition, air oxidation, and reduction by hydrogen, and of the air oxidation of ferrous sulphide between 420° and 650° C. have been studied by Schwab and Philinis.[1] Reviews of numerous investigations of the reactions involved in the roasting and flash-roasting of pyrites and practical aspects of operation and equipment have also been published.[2–4] However, the exact mechanism of the oxidation of pyrites during roasting is not yet established. The reaction is usually summarized as:

$$4FeS_2 + 11O_2 = 2Fe_2O_3 + 8SO_2 \quad \ldots\ldots(1)$$

but there are numerous intermediate steps possible:

$$FeS_2 = FeS + S \text{ (above 600° C.)} \quad \ldots\ldots(2)$$

$$S + O_2 = SO_2 \quad \ldots\ldots(3)$$

$$4FeS + 7O_2 = 2Fe_2O_3 + 4SO_2 \quad \ldots\ldots(4)$$

Other oxides of iron can also be formed.

Since the sinter mix contains free and combined water, the following reactions are also possible:

$$3FeS_2 + 2H_2O = 3FeS + 2H_2S + SO_2 \quad \ldots\ldots(5)$$

$$FeS + H_2O \rightleftharpoons FeO + H_2S \quad \ldots\ldots(6)$$

Although the presence of steam may seem improbable at the high temperatures involved in sintering, it should be remembered that at the rapid heating rates (up to 100° C./sec.)[20] during sintering the evolution of combined water from the centre of large ore lumps may take place even when the surface temperature of the lumps is very high.

The extraction of sulphur from carbon-containing pyrites by burning in insufficient air with the simultaneous introduction of water vapour has been investigated by Postnikov and Kirillov,[5] whose results, like those of Thompson and Tilling,[6] indicated that the removal of sulphur at temperatures up to 700° C. is improved by steam, but at higher temperatures the presence of water decreases the rate of this reaction.

The combustion of pyritic sulphur is a strongly exothermic reaction and in a sinter mix pyrites may form part of the fuel. On a thermal basis 1·6% of pyritic sulphur has been found to be equivalent to 1% of coke,[7] and the ignition temperature of pyrites is comparable with that of coke.[8]

REACTIONS OF CALCIUM SULPHATE

Preliminary experiments had shown that pyritic sulphur was easily oxidized during sintering and that

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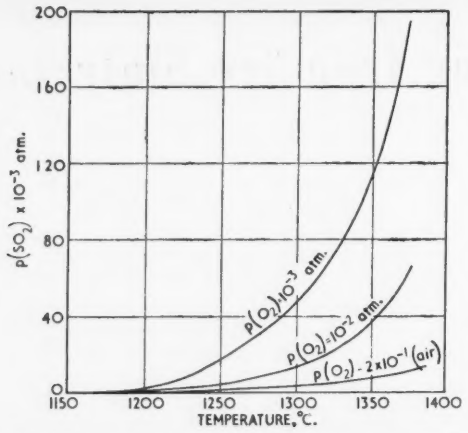


Fig. 1—Influence of partial oxygen pressure and temperature on the equilibrium partial pressure of SO_2 on thermal decomposition of $CaSO_4$

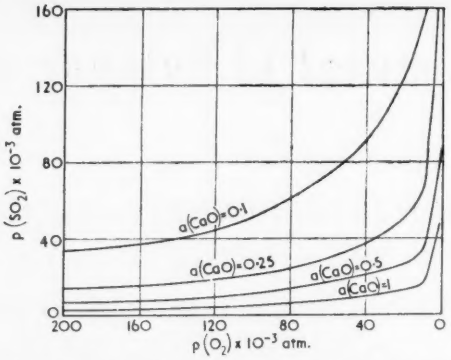


Fig. 2—Influence of lime activity and partial oxygen pressure on the equilibrium partial pressure of SO_2 at 1300° C.

if lime or limestone were absent the sulphur dioxide produced was removed with the waste gas. However, if lime or limestone is present in the mix it absorbs part of the sulphur dioxide, forming calcium sulphate. Therefore when the oxidation of pyrites is complete the residual sulphur in the mix is in the form of calcium sulphate and its further removal will depend on the rate of decomposition of this compound. This simplified picture of sulphur removal is only true if the oxygen pressure during this period of sintering is above 10^{-5} atm.[9] At lower oxygen pressures calcium sulphate is unstable and decomposes to calcium sulphide and oxygen. Although the composition of the waste gas does not correspond to such a low oxygen pressure, it may well be attained in the neighbourhood of incandescent carbon particles. Calcium sulphide is stable under reducing conditions and further removal of sulphur requires oxidizing conditions or, possibly, reaction with water vapour[10]:

$$CaS + H_2O \rightleftharpoons CaO + H_2S \quad \ldots\ldots\ldots\ldots\ldots (7)$$

Provided that the particle size of the sulphide material is sufficiently small for the pyrites to be oxidized in the time available, the whole problem of sulphur removal therefore depends on the formation and decomposition of calcium sulphate.

The behaviour of calcium sulphate has been investigated by many workers. A review of these investigations was given by Bedwell,[11] and it will be sufficient here to discuss the main reactions only.

Thermal Decomposition of Calcium Sulphate

$$2CaSO_4 \rightleftharpoons 2CaO + 2SO_2 + O_2 \quad \ldots\ldots\ldots\ldots\ldots (8)$$

The direction and velocity of this reaction will depend on the dissociation pressure of calcium sulphate and the partial pressures of oxygen and sulphur dioxide. The dissociation pressure of calcium sulphate was measured by Marchal[12] and by Zawadski[13] and was found to be small (e.g. at 1200° C. the total pressure of gaseous products = 0·08 atm.), and therefore thermal dissociation in air is unlikely to cause appreciable sulphur elimination during sintering. However, the presence of carbon will reduce the oxygen pressure and with continuous removal of the gaseous decomposition products by the waste gases this reaction may be fast. The influence of the partial pressures of gaseous decomposition products can be seen from the equation for the equilibrium constant (K):

$$K = \frac{a^2(CaO).p^2(SO_2).p(O_2)}{a^2(CaSO_4)} = p^2(SO_2).\ p(O_2)$$

(for pure CaO and $CaSO_4$)

where a is activity and p partial pressure. Thus when the partial pressure of oxygen decreases, reaction (8) will proceed to the right. To illustrate the quantitative

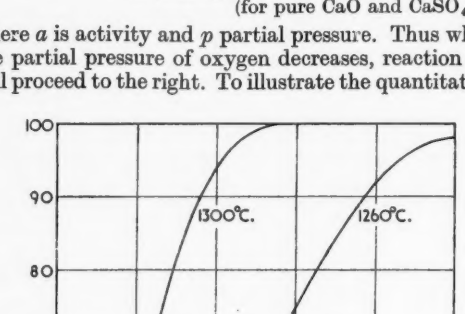


Fig. 3—Evolution of sulphur on interaction of $CaSO_4$ with Fe_2O_3 at 1217°, 1260°, and 1300° C.

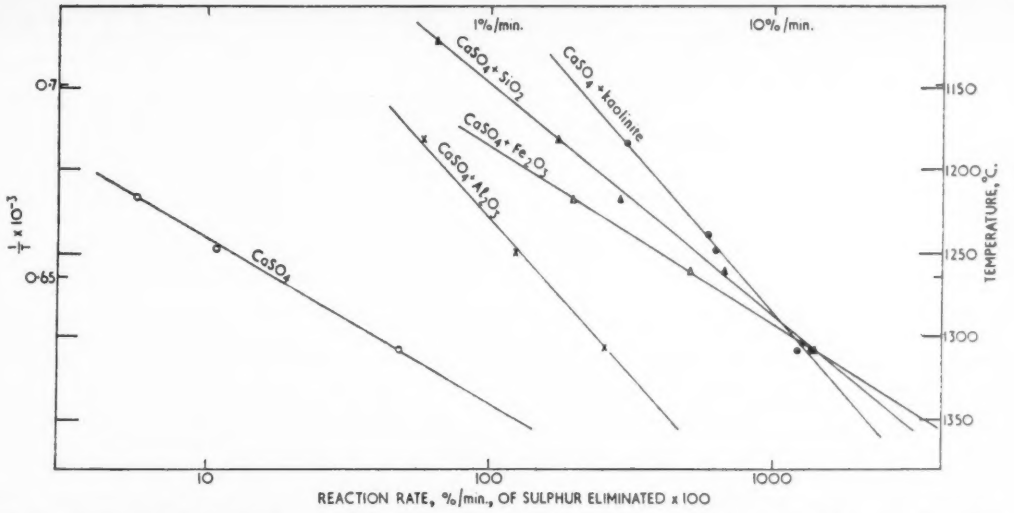


Fig. 4—Temperature dependence of the reaction rates of $CaSO_4$ with Al_2O_3, Fe_2O_3, SiO_2, and kaolinite, and thermal decomposition of $CaSO_4$ ignited in an alumina boat

influence of oxygen pressure on the partial pressure of SO_2, the equilibrium SO_2 pressures for various oxygen pressures have been plotted against temperature in Fig. 1 (calculated from equilibrium constants at various temperatures[14]).

As can be seen from Fig. 1 the influence of oxygen pressure on the equilibrium SO_2 pressure of calcium sulphate is very great. The extent to which oxygen pressure can be lowered in a given volume of a mix during sintering depends on the amount and distribution of carbon particles and the intensity of their combustion, so that these factors should exert a strong influence on sulphur elimination. It is known from practice[7, 15, 16] that for given sintering conditions there is an optimum carbon content for which the amount of sulphur removed is at a maximum.

Reactions of Calcium Sulphate with Silica, Alumina, and Ferric Oxide

The formation of calcium silicates, ferrites, and aluminates will decrease the activity of calcium oxide, thus increasing the equilibrium SO_2 pressure. The influence of the activity of calcium oxide is shown in Fig. 2, in which the equilibrium SO_2 pressure at 1300° C. has been replotted against oxygen pressure for various values of calcium oxide activity.

It might be expected that, since the free energies of formation of dicalcium silicate, dicalcium ferrite, and calcium aluminate are −30, −16, and −5 kcal./mol., respectively,[17] their influence on the decomposition of calcium sulphate should decrease in the same order. This was confirmed by Hofman and Mostowitsch[18] and Neumann.[19] However, the equilibrium pressures of the gaseous decomposition products cannot give any definite information on the kinetics of the various reactions, and since the reaction time (i.e. time above 1000° C.) in the sintering process is limited to 1–2 min.,[20] reaction velocities are of particular importance. For this reason the thermal dissociation of calcium sulphate and the velocity of calcium sulphate reactions with the main components of a sinter mix (SiO_2, Al_2O_3, Fe_2O_3, and clay) has been investigated under specified laboratory conditions.

The kinetics of the reaction of calcium oxide and carbonate with ferric oxide were investigated by Konarzewski.[21] who found that this reaction proceeds at an appreciable rate at 650° C.

EXPERIMENTAL INVESTIGATION

KINETICS OF CALCIUM SULPHATE REACTIONS

Mixtures of calcium sulphate with silica, ferric oxide, alumina, and clay were prepared in which the molecular ratio of calcium oxide to these oxides was unity. In the sulphate–clay (kaolinite) mixture the lime/silica ratio was also unity.

The experimental method used was as follows: pure components were used, all ground −100 mesh and well mixed in a ball mill. A weighed sample of the mixture to be investigated (e.g. $CaSO_4 + SiO_2$) was placed in an aluminous porcelain boat and introduced into a tube furnace held at a given temperature, and a stream of air (2·8 l./min. at N.T.P. ≡ 60 cm./sec. at 1200° C. through the tube) was passed over it. On leaving the furnace the air stream was passed through a column of water in which any sulphur dioxide, evolved from the sample, was absorbed and continuously titrated with N/10 sodium hydroxide solution in the presence of methyl orange as an indicator.

The reproducibility of repeated experiments was good (± 3·5%) and the accuracy of temperature measurements was within ± 10° C. Some loss of sulphur (max. 8% of total) occurred, particularly when the evolution was very rapid; however the results obtained are considered sufficiently accurate for comparative purposes. By plotting the amount of sulphur evolved against time, curves were obtained from which the reaction rates could be calculated. An example of the results obtained is shown in Fig. 3. Since it was previously ascertained that the required temperature of the sample is attained in 2–2·5 min.

Table I

DESULPHURIZATION OF BRIQUETTES CONTAINING NO LIME

Sulphur Content, %		Sulphur Removed, %	Ignition Temperature, °C.
Before Ignition	After Ignition		
2·47	0·0206	99·0	1150
2·47	0·0193	99·1	1200
2·47	0·0136	99·3	1250
2·47	0·023	98·6	1150*

* Heated to 1150° C. in 5 min. and removed from the furnace

after it is introduced into the furnace, the part of the curve representing the evolution of sulphur during this initial period could not be used for the calculation of the reaction rates. To obtain comparable data, rates of sulphur evolution between 25% and 50% were calculated. The results are shown in Fig. 4, where log rate is plotted against the reciprocal of absolute temperature.

Figure 4 shows that the velocity of thermal dissociation of calcium sulphate in the absence of carbon is low (about 2·5% per min. at 1400° C.) and therefore has no practical influence on the removal of sulphur. For similar reasons the reaction of calcium sulphate with alumina may be also disregarded. The reaction rate of calcium sulphate with ferric oxide at temperatures below 1300° C. is slightly lower than with silica, but becomes higher at temperatures above 1300° C. Since iron oxide is the main component of sinter mixes the formation of calcium ferrites is particularly important. The reactions of calcium sulphate with kaolinite are also of great interest since clay is an important component of home ores.

REMOVAL OF SULPHUR FROM SINTER MIXES

Influence of Fe_2O_3, CaO, and SiO_2 on Sulphur Removal

All sinter mixes were artificially prepared from pure components, ground to −100 mesh, weighed, and mixed, first by hand and then in a ball mill for a standard time of 1 hr. The following materials were used: Itabera iron ore (98% Fe_2O_3, 1·7% Al_2O_3, 0·36% SiO_2); pure fused silica; pure lime; pure anhydrite ($CaSO_4$); iron pyrites (48·5% S); and marble ($CaCO_3$). The initial sulphur content of all sinter mixes was 2·5%.

To avoid the use of containers, which in preliminary experiments showed a marked reaction with the sinters and restricted the circulation of air, sinter mixes containing 10% of moisture were compressed into flat briquettes ($\frac{7}{8}$ in. dia., $\frac{3}{16}$ in. height) under a pressure of 1000 lb./sq. in. The briquettes produced were just strong enough to be handled. The briquettes were supported on refractory knife-edges and placed in a vertical tube furnace under natural draught. The briquettes were lowered into the hot zone of the furnace at a standard rate so that the temperature of the briquettes was raised to 1150 ± 10° C. in 5 min.

Sintering was continued for a further 20 min. at this temperature. At the end of this time the briquettes were withdrawn from the furnace, cooled in air, and analysed for sulphur. The choice of the temperature and time of sintering was based on the following:

(i) Although the temperature of 1150° C. is much lower than that of a normal sintering process, it is sufficient to remove pyritic sulphur from lime-free mixes

(ii) At this temperature thermal decomposition of the calcium sulphate formed is very small

(iii) Acid mixes ($CaO/SiO_2 < 1$) undergo a considerable fusion just above 1150° C., and this was avoided because such fusion might complicate the comparison of results obtained from fused and non-fused briquettes

(iv) The sintering time of 25 min. was chosen to compensate for small temperature variations which in a shorter sintering period might introduce additional errors

(v) The rate of the initial heating could not be increased owing to an explosive evolution of water, which shattered briquettes heated at a higher rate.

To determine the maximum degree of possible sulphur elimination under these experimental conditions, some briquettes of Itabera ore with a suitable addition of pyrites to give 2·5% S and no lime were ignited. To minimize the thermal decomposition of $CaSO_4$, formed by absorption of SO_2, sinter mixes free from carbon were used. The results are given in Table I, which shows that at 1150° C. 99% desulphurization takes place and any further increase in temperature has little practical influence on the desulphurization of these briquettes.

In the next two series of experiments briquettes from mixes containing 5, 10, 15, and 20 wt.-% of CaO in the form of lime or carbonate and no silica were ignited. The results are plotted in Fig. 5 and indicate the major influences of lime concentration in the sinter mix on the amount of pyritic sulphur which can be transformed into calcium sulphate.

For further experiments a number of mixes were prepared in which the lime concentration was varied from 2·5 to 20 wt.-% and the lime/silica ratio from 0·33 to 1·3. The results of all experiments are given in Table II.

X-ray powder photographs were made which showed that free lime was present in all sinters, except those whose basicity was below 0·75. Free silica, calcium ferrites, and dicalcium silicate

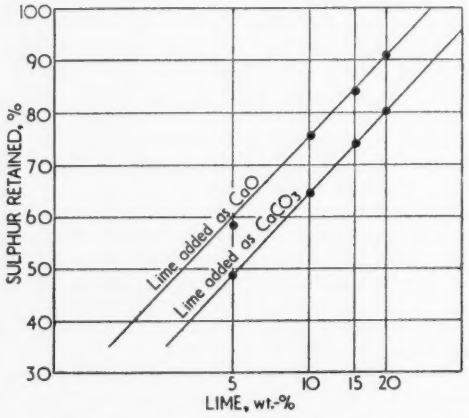


Fig. 5—Influence of lime concentration on percentage of sulphur retained after ignition under experimental conditions

were found in all sinters examined. Sulphur was present as calcium sulphate, but owing to its low concentration its X-ray diffraction pattern was not well defined.

Since dolomite may be present in sinter mixes the influence of magnesium oxide on the retention of sulphur was also studied. A mix containing 14·4% MgO with the molecular ratio of $MgO/SiO_2 = 1·39$ was ignited. The percentage of sulphur eliminated was 98·7% (mean of three determinations). Thus it can be stated that magnesium oxide has no practical influence on the elimination of pyritic sulphur during sintering.

The results of these experiments are summarized in Fig. 6, in which the iso-sulphur lines (equal percentage of retained sulphur) are plotted in the iron-oxide-rich corner of the Fe_2O_3–CaO–SiO_2 system. These results do not represent the actual amount of sulphur which may be retained under normal sintering conditions, since carbon was not present in the mixes and the temperature and rate of heating were not those of a normal sintering process. Nevertheless, these results indicate the importance of lime concentration on the amount of pyritic sulphur which may be absorbed in the mix and transformed into calcium sulphate. The distribution of the iso-sulphur lines shows that in acid mixes ($CaO/SiO_2 < 1$) the concentration of lime is more important than the lime/silica ratio. In basic mixes ($CaO/SiO_2 > 1$), however, the influence of lime/silica ratio increases rapidly with increasing basicity (density of iso-sulphur lines increases).

On the basis of the available evidence, it appears that the process of the removal of pyritic sulphur during sintering proceeds in three stages: oxidation of pyrites with the evolution of sulphur dioxide, absorption of sulphur dioxide by lime with the formation of calcium sulphate, and the decomposition of calcium sulphate. These three stages of the process do not proceed successively but overlap and at higher temperatures proceed simultaneously. The proportion of the initial sulphur retained in the sinter depends on the kinetics of these three processes, and in particular on the availability of lime during the oxidation of pyrites. For this reason the concentration of lime and the form in which it is present is important. On the other hand, the lime/silica ratio begins to be an important factor mainly in the third stage of the process (decomposition of calcium sulphate).

Assuming that no free lime is present in a sinter mix the kinetics of the oxidation of pyrites are of primary importance. Oxidation begins at about 420° C. and,

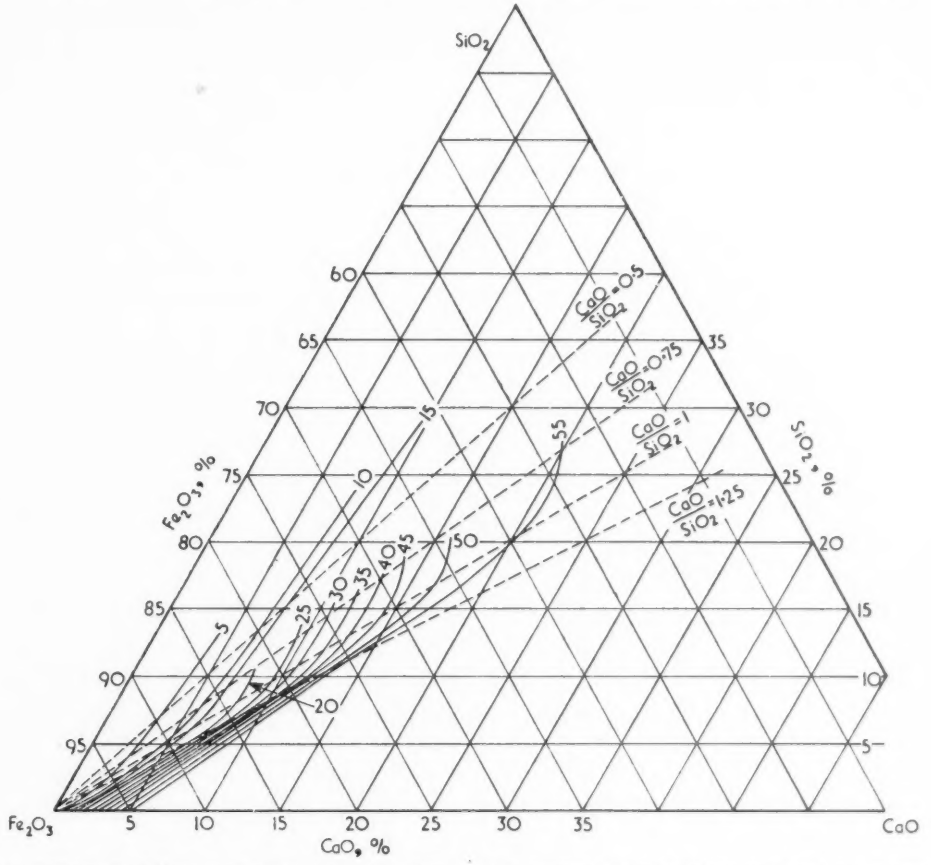


Fig. 6—Influence of lime and silica concentrations on the percentage of sulphur retained in a sinter mix after ignition under experimental conditions

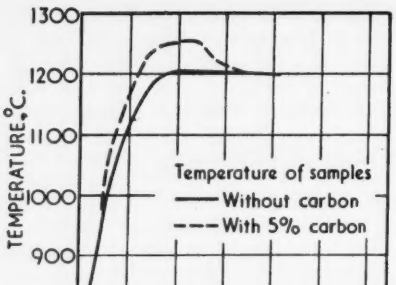
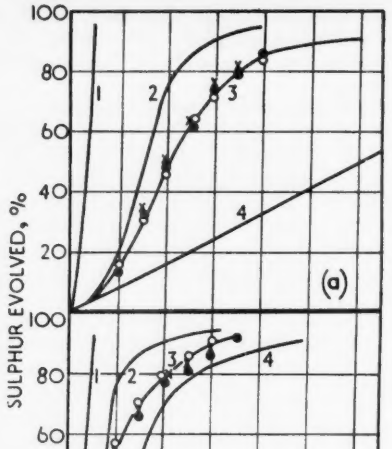


Fig. 7—Rate of heating of samples investigated

if the reaction is well advanced before the decomposition of limestone begins, the amount of sulphur absorbed by lime will be small. Therefore, in further research on the subject the experimental technique was so modified as to permit measurements of the actual rate of sulphur elimination.

Rate of Evolution of Sulphur

In this series of experiments the evolution of sulphur from various synthetic iron oxide sinter mixes with and without carbon and all containing 2·5% of sulphur was investigated. Acheson electrode carbon was used as a source of carbon. The technique was similar to that used for measuring the kinetics of $CaSO_4$ reactions. Mixes containing carbon would be expected to have a different rate of heating under the experimental conditions from those without and the



1. No lime
2. 5% lime; CaO/SiO = 0·33
3. 5% lime; ○ $CaO/SiO_2 = 0·75$ × $CaO/SiO_2 = 1·0$ ● $CaO/SiO_2 = 1·25$
4. 5% lime, no silica

Fig. 8—Evolution of sulphur from mixes containing 2·5% pyritic sulphur: (*a*) no graphite, (*b*) 5% graphite

Table II

DESULPHURIZATION OF BRIQUETTES CONTAINING VARIOUS PERCENTAGES OF LIME AND SILICA

Lime, wt.-%	Silica, wt.-%	CaO/SiO_2 Ratio	Sulphur in Raw Mix, %	Sulphur Content, %	Sulphur Retained, %	Remarks
5	...	...	2·5	1·45	58·0	Mean of 2 determinations
10	...	...	2·5	1·89	75·5	" " "
15	...	...	2·5	2·10	84·0	" " "
20	...	...	2·5	2·29	91·0	" " "
20	40·0	0·5	2·41	1·40	58·3	Mean of 15 determinations
20	20·0	1·0	2·36	1·28	54·2	Mean of 18 determinations
20	15·3	1·3	2·42	1·66	68·5	Mean of 9 determinations
5	6·66	0·75	2·5	0·37	14·8	Mean of 3 determinations
5	5·0	1·0	2·3	0·26	11·3	" " "
5	4·0	1·25	2·3	0·25	10·9	" " "
10	13·3	0·75	2·5	0·66	26·4	" " "
10	10·0	1·0	2·5	0·67	26·8	" " "
10	8·0	1·25	2·4	0·85	35·4	" " "
15	20·0	0·75	2·5	1·26	50·4	" " "
15	15·0	1·0	2·5	1·17	46·8	" " "
15	12·0	1·25	2·5	1·57	62·5	" " "
2·5	7·57	0·33	2·5	0·08	3·2	" " "
5·0	15·12	0·33	2·5	0·15	6·0	" " "
7·5	22·7	0·33	2·5	0·228	9·1	" " "
10	30·3	0·33	2·5	0·415	16·6	" " "
Mixes with lime in the form of carbonate						
5	...	...	2·5	1·21	48·5	" " "
10	...	...	2·5	1·61	64·5	" " "
15	...	...	2·5	1·85	74·0	" " "
20	...	...	2·5	2·00	80·0	" " "

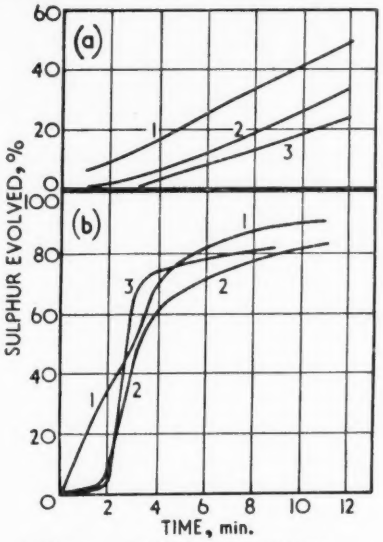
extent of this effect is shown in Fig. 7. These temperature/time curves were plotted on the basis of average values obtained from many determinations. The differences between individual determinations were of the order of $\pm 15°$ C.

Influence of Lime Concentration and Lime/Silica Ratio

The rates of sulphur evolution from the various mixes are presented in the form of curves drawn on the basis of average results from three separate determinations. In Figs. 8*a* and *b*, the evolution of sulphur from mixes containing 5% of lime and various amounts of silica, with and without carbon, respectively, is shown. For comparison the evolution of sulphur from a mix containing no lime is also plotted.

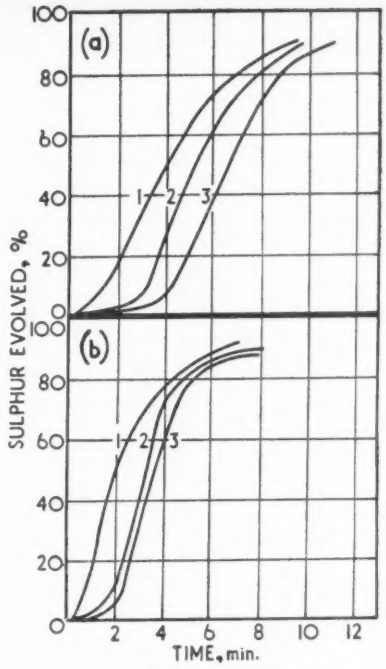
Curve 1 indicates that the oxidation of pyrites is very fast and that practically all the sulphur is removed before the temperature of the sample reaches about 1050° C. The presence of carbon had no apparent effect on the velocity of oxidation. However, at high rates of evolution titration could not be done sufficiently quickly to differentiate time-intervals of 10–15 sec.

Comparison of curve 1 with other curves in Figs. 8*a* and *b* shows that any sulphur retained in the sinter mix after the first minute of sintering has been transformed into sulphate sulphur, i.e. the SO_2 evolved during the oxidation of pyrites has been absorbed by lime. The other curves show that the amount of sulphur so retained is independent of the lime/silica ratio, but is related to the concentration of lime and to the amount of carbon present (oxygen pressure). In mixes without carbon 95%, and in mixes with carbon, 80% of sulphur was retained after the first minute. The variation in lime/silica ratio within the narrow limits 0·75–1·25 affected the rate of sulphur evolution (curve 3) only to a degree which was within the limits of experimental error, but the importance of this factor is shown by the effect of large variations in the lime/silica ratio: 0·33 (curve 2) and ∞ (curve 4). As expected from thermodynamic considerations, the influence of carbon is predominant and causes the gap between the individual curves to be considerably decreased (*see* Figs. 8*a* and *b*).



1. 5% lime 2. 10% lime 3. 15% lime

Fig. 9—Evolution of sulphur from mixes containing 2·5% pyritic sulphur; (*a*) no graphite, (*b*) 5% graphite. No silica added



1. 5% lime 2. 10% lime 3. 15% lime

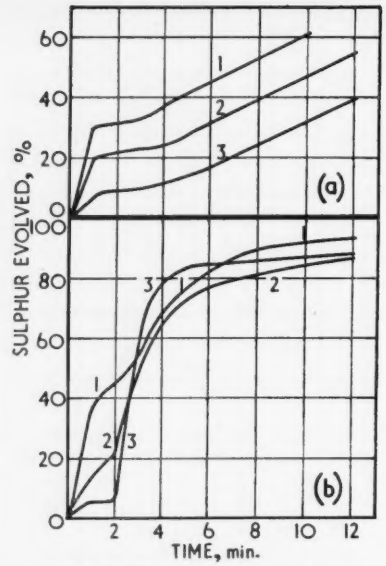
Fig. 10—Evolution of sulphur from mixes containing 2·5% pyritic sulphur; (*a*) no graphite, (*b*) 5% graphite. CaO/SiO_2 ratio = 1

In Figs. 9 and 10, the influence of lime concentration, with and without silica, on the rate of sulphur evolution is shown. With an increase in lime concentration the amount of sulphur evolved in the first minute of sintering decreases. With 10% of lime and no carbon (Fig. 9*a*, curve 2) almost all the original pyritic sulphur is converted into sulphate sulphur.

By comparing the average slopes of the curves in Figs. 9*a* and 10*a* the influence of the silica addition can be assessed. The average rate of sulphur evolution from mixes with a lime/silica ratio of 1 was approximately five times faster than from those without silica. However, on the addition of carbon the difference in the reaction rates was considerably lessened, owing to the predominant influence of the thermal dissociation of calcium sulphate.

It is interesting to note another factor influencing the rate of sulphur evolution—the appearance of a liquid phase. Incipient melting was observed in all sinters, but sinter mixes containing 15% of lime and 5% of carbon were completely slagged. The influence of melting is reflected in the rate of sulphur evolution from this mix (Fig. 9*b*, curve 3). Nearly 70% of the sulphur was evolved between the second and third minutes of the experiment, which is much higher than for any other mix.

Calcium oxide, or rather slaked lime, is present in a



(1) 5%, (2) 10%, (3) 15% CaO as carbonate

Fig. 11—Evolution of sulphur from mixes containing 2·5% pyritic sulphur; (*a*) no graphite, (*b*) 5% graphite. No silica present

sinter mix only if added to improve its sintering characteristics. The usual form in which lime is present is limestone or dolomite. The experimental work showed that the presence of magnesia had no appreciable influence on the evolution of sulphur during sintering. Therefore, in the next series of experiments, calcium carbonate (marble) was used as a source of lime.

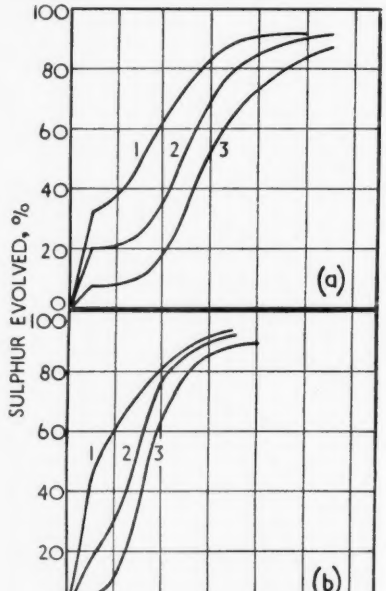
In Figs. 11 and 12 the evolution of sulphur from mixes with lime in the form of carbonate is plotted. The relationship between the rates of sulphur evolution from these mixes was similar to that obtained with mixes containing calcium oxide (Figs. 9 and 10), except for the amount of sulphur evolved during the first minute of the sintering process. Owing to the lower lime activity of the carbonate, less of the sulphur dioxide evolved in the oxidation of pyrites was absorbed and transformed to calcium sulphate.

Influence of Heating Rate on Removal of Pyritic Sulphur

The influence of the rate of heating on the evolution of pyritic sulphur was investigated by placing samples of a mix (containing 10% lime, 10% silica, 2·5% pyritic sulphur, and 5% carbon) in the furnace held at 1200° or 1300° C., thus giving two different rates of heating. In the first minute the samples reached about 1020° and 1060° C., and the mean heating rate after this was 75 C. deg./min. and 130 C. deg/min., respectively. At the higher heating rate the time required for over 90% elimination of sulphur was nearly halved (from 6½ to 3 min.) and the amount of sulphur dioxide evolved during the first minute (i.e. that which escaped re-absorption by lime) increased from about 3% to 30%. Therefore the rate at which the temperature of the flame front zone increases has a substantial influence on the desulphurization process during sintering. With increasing heating rates, the rate of sulphur evolution increases, particularly in the first minute of sintering.

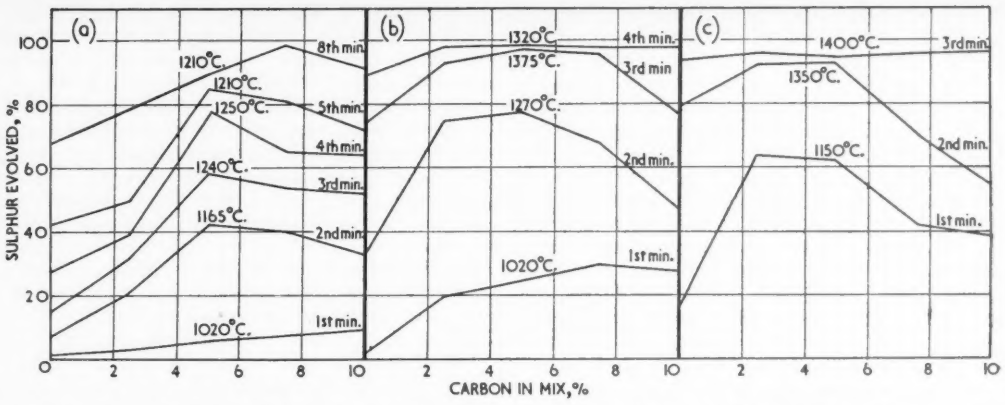
Influence of Carbon Content on Removal of Sulphur

One of the main factors in the removal of sulphur during sintering is the decomposition of calcium sulphate either present initially in the sinter mix or formed in the early stages of sintering by the reaction between lime and the sulphur dioxide evolved in the oxidation of pyrites. This decomposition is strongly affected by oxygen pressure during sintering (*see* Fig. 1), which in turn depends on the amount of carbon in the sinter mix. With decreasing oxygen pressure, the rate of decomposition of $CaSO_4$ is rapidly increased, but when the oxygen pressure falls below 10^{-5} the reduction of sulphate to sulphide occurs and decreases the rate of sulphur removal. Although the composition of the waste gas does not suggest the possibility of such a low oxygen pressure, this may occur in the neighbourhood of incandescent carbon particles. To study this effect the rates of sulphur evolution from mixes containing 2·5% of sulphate sulphur (CaO = 5%, SiO_2 = 5%; CaO/SiO_2 = 1) and various amounts of carbon (0–10%) were ignited at three different rates of heating. The results are shown in Figs. 13*a–c*, in which the percentages of sulphur evolved during successive minutes of sintering at different heating rates are plotted against the carbon content of the mix. This diagram clearly shows that for given sintering conditions there is an optimum carbon content at which the rate of sulphur evolution is a maximum.



(1) 5%, (2) 10%, (3) 15% CaO as carbonate

Fig. 12—Evolution of sulphur from mixes containing 2·5% pyritic sulphur; (*a*) no graphite, (*b*) 5% graphite. CaO/SiO_2 ratio = 1



(*a*) Slow heating; furnace temperature 1210° C. (*b*) Medium heating; furnace temperature 1320° C. (*c*) Fast heating; furnace temperature 1400° C.

Fig. 13—Influence of carbon content and temperature conditions on the evolution of sulphate sulphur. Temperatures on curves refer to 5% carbon mixture at the stated times

This optimum carbon content depends on the final temperature and the rate of temperature increase (i.e. on the intensity of combustion) which in turn will depend on the amount of air passing through the sinter bed, the extent of endothermic reactions, and the degree of preheat. With increasing heating rates the optimum carbon content moves towards lower values.

It is known from sinter-plant practice that the degree of oxidation of a sinter is positively correlated with the degree of removal of sulphate sulphur.[16] Results reported by Astier of the works trials of the desulphurization of Khenifra ore during sintering illustrate this effect:

Degree of oxidation, %	92	91	91	85	85	81	78
Desulphurization, %	88	88	89	86	80	76	66

Influence of Moisture on Removal of Sulphur

The possibility of the occurrence of reactions between sulphide and water during sintering was also investigated. The experimental procedure was as before, except that air before entering the reaction tube was saturated with water vapour at 45° C. ($p(H_2O) = 71$ mm.). The composition of the mix and the temperature were the same as in Fig. 8*b*, curve 3. The rate of sulphur evolution in moist air was slightly higher than that in dry air. The differences, however, were within the limits of experimental error, except for the amount of sulphur evolved in the first minute, which was about 5% higher, i.e. just outside the experimental error. This suggests that the rate of oxidation of pyrites may be higher in the presence of moisture, but the evidence is not conclusive.

The influence of moisture on the evolution of sulphate sulphur was examined using a sinter mix containing 2·5% of sulphate sulphur and 10% of carbon (CaO, 5%; SiO_2, 5%). The ignition temperature was 1350° C. These conditions were chosen to promote the formation of calcium sulphide. The results were again inconclusive, since the differences in the rate of sulphur evolution with dry and moist air were within the limits of experimental error.

The introduction of moisture into the sinter mix itself was impossible under the experimental conditions, since owing to high heating rates its evaporation was explosive. This explosive evaporation of water should promote the removal of sulphur in actual practice, since ore lumps will be fissured, thus opening enclosed pyrites to oxidation.

In practice the moisture in the lower part of the bed can dissolve some of the SO_2 liberated higher up, thus increasing the sulphur content in the lower layers. This phenomenon results in the bulk of the sulphur being eliminated during the final stages of sintering.[22]

DISCUSSION OF RESULTS

On the basis of the experimental evidence and theoretical considerations, the following mechanism of sulphur elimination during sintering may be postulated. When the approaching flame front raises the temperature of a layer of the sinter mix to above 400° C., pyritic sulphur begins to oxidize and the rate of oxidation rapidly increases with increasing temperature. A rapid evaporation of moisture and the evolution of combined water may assist this oxidation, mainly through the creation of favourable physical conditions by fissuring ore lumps and exposing the pyrites. The presence of water vapour may also increase the rate of sulphur elimination. Provided that the particle size of the pyrites is small, their oxidation may be complete before a temperature of 1000° C. is reached. The sulphur dioxide produced is partly removed from the hot zone by the waste gases. Judging from experimental results, even 5% of lime is sufficient to absorb nearly all the sulphur dioxide produced, particularly as in practice this absorption takes place not only in the reacting zone, but also in the layers situated below the flame front.[22] Sulphur dioxide absorbed by lime is transformed to calcium sulphate and further elimination of sulphur only takes place by the decomposition of this compound. When the temperature exceeds 1000° C. the velocity of decomposition of calcium sulphate becomes appreciable and it can proceed together with the oxidation of the remaining pyrites. This decomposition may take place either by thermal dissociation accelerated by low oxygen pressures near to incandescent carbon particles or by reactions with clay,

silica, and ferric oxide. Sulphate particles in proximity to a carbon particle may be reduced to calcium sulphide, whilst other particles situated further away may be decomposed to calcium oxide, sulphur dioxide, and oxygen, owing to the favourable oxygen pressure of their immediate atmosphere. It is therefore probable that during sintering a certain proportion of calcium sulphate is reduced to sulphide, and the amount so transformed must be some function of the carbon content of the sinter mix when other sintering conditions remain constant. Sulphur from the calcium sulphide so formed may be removed later by reoxidation, as the oxygen pressure increases with the consumption of carbon, or it may be trapped in slag envelopes. The latter may easily occur if a fluid ferrous slag, in which sulphides are dissolved or suspended, is oxidized on the surface and forms a solid envelope owing to a sudden increase in its melting point.

This mechanism of sulphur removal may be summarized by the following chemical equations:

$$4FeS_2 + 11O_2 = 2Fe_2O_3 + 8SO_2 \quad \ldots\ldots(1)$$

$$2CaO + 2SO_2 + O_2 \rightleftharpoons 2CaSO_4 \quad \ldots\ldots(8)$$

$$CaSO_4 + 2C = CaS + 2CO_2 \text{ (when } p(O_2) < 10^{-5} \text{ atm.)} \quad \ldots\ldots(9)$$

$$CaS + 2O_2 = CaSO_4 \text{ (when } p(O_2) > 10^{-5} \text{ atm.)} \quad \ldots(10)$$

$$CaSO_4 + Fe_2O_3 = CaO.Fe_2O_3 + SO_2 + \tfrac{1}{2}O_2 \quad \ldots(11)$$

$$2CaSO_4 + SiO_2 = 2CaO.SiO_2 + 2SO_2 + O_2 \quad \ldots\ldots(12)$$

Considering the individual reactions in the light of experimental evidence, it can be stated that reaction (1) is fast and, provided that the particle size of the pyrites is small and that they are not enclosed in ore lumps or slag envelopes, the time available for reaction is sufficient for almost complete sulphur removal. In the experiments using finely divided materials, pyritic sulphur was removed from sinter mixes containing no lime in less than 1 min., but the actual time of intensive evolution of sulphur dioxide was 10–20 sec.

Reactions (8) and (9) seem to be the key to the desulphurization process in sintering. In the initial stages of sintering and in the layers of the sinter mix below the flame front reaction (8) proceeds to the right, leading to the absorption of sulphur already evolved and the formation of calcium sulphate. The amount of sulphur so re-absorbed depends on the partial pressure of the gaseous products, the availability of lime, and the form in which it is present. Lime added to sinter mixes to improve their sintering quality will be most efficient in absorbing sulphur dioxide, since when well mixed it will form calcium hydroxide coatings on the ore and coke particles, thus presenting a large surface. The re-absorption of sulphur in the flame front zone may be diminished by the formation of calcium ferrites and silicates. The high temperatures at which these reactions proceed rapidly may during sintering be attained before the whole of the pyrites is completely oxidized, so that the effect may be twofold: the amount of available lime for the absorption of SO_2 may be diminished and some of the calcium sulphate either originally present or formed in the sintering mix may be decomposed (reactions (11) and (12)).

Reaction (8) will proceed to the left at the low oxygen pressures caused by incandescent carbon particles. As shown by the experimental results, thermal decomposition of calcium sulphate in the presence of carbon is the main reaction by which sulphate sulphur is removed. However, in the immediate neighbourhood of incandescent carbon particles, reaction (9) may take place, which will slow down the removal of sulphur, since for its further elimination reaction (10) must occur. The extent of reaction (9) depends on the carbon content of the mix and the intensity of its combustion (Figs. 13*a–c*). The importance of this reaction is particularly well illustrated in Fig. 13*c*. Comparing the amount of sulphur evolved in the first 2 min. of ignition from the mix without carbon and those with 7·5% and 10% of carbon shows that in the latter two cases the influence of carbon was negative. Whilst the carbon-free mix lost 80% of its sulphur mainly by reactions with ferric oxide and silica (reactions (11) and (12)), the other two mixes lost only 72% and 55%, respectively. Thus the reduction of sulphate to sulphide hindered the evolution of sulphur very considerably. Although the removal of sulphur from the last two mixes increased in the third minute with the consumption of the carbon, this may not necessarily happen in practice. In the experiments the high temperature of the samples was maintained by a hot furnace, but in practice the peak temperature will rapidly decrease following the consumption of the carbon, and the sulphur not already evolved may be trapped in slag envelopes.

The other factor which increased the rate of sulphur evolution was the appearance of a liquid phase. In all cases when ignited sinter mixes were extensively slagged, the rate of sulphur evolution was higher (curve 3, Figs. 9*b* and 10*b*). Since reducing conditions for all three curves in Figs. 9*b* and 10*b* were similar, the influence of slagging must be related to an increase in the rates of reactions (11) and (12), which depend greatly on the contact area. The appearance of a liquid phase improves the contact between lime and calcium sulphate with other components promoting the formation of calcium ferrites and silicates, i.e. the evolution of sulphur. On the other hand, extensive slagging may increase the amount of sulphur trapped in slag envelopes.

An increase in the maximum temperature reached in sintering increased the rate of sulphur evolution, but in all experiments in which ignition temperature was raised to 1300° C. the influence of the temperature and of the appearance of the liquid phase were superimposed.

It was mentioned that lime added to a sinter mix to improve its sintering characteristics, when properly mixed, will form a calcium hydroxide coating on the particles of the sinter mix. No satisfactory explanation has been offered for the action of lime in improving the sintering characteristics of some sinter mixes, and particularly of Sierra Leone concentrates. Gledhill *et al.*,[23] who investigated the influence of lime additions to sinter mixes made from Sierra Leone concentrates and return fines only, found that the increase in the pre-ignition permeability was negligible, whereas the improvement in sintering (sintering time

and the amount of air required) was considerable. One possible reason for this improvement is the lime coating on the individual hematite grains, which produces a very large reacting surface for the solid–solid reaction between calcium oxide and ferric oxide forming calcium ferrite. Calcium monoferrite melts at about 1200° C., transforming into dicalcium ferrite, so that an incipient melting takes place on the surface of the hematite grains, causing sintering to take place at a much lower temperature than otherwise would be required.

If this explanation is correct, the sulphur dioxide absorbed by the lime coating on ore grains should be easily removed by reactions (11) and (12), whilst sulphur absorbed on the coating of coke particles will be initially reduced to sulphide and can be removed only after the carbon is consumed at least to some extent. Therefore in such cases when a lime addition for improving sintering properties of a mix is necessary it would seem advisable to mix ore with lime before the coke addition is made. This may diminish the proportion of coke coated with lime.

Despite the purely laboratory character of this work, it gives evidence of how the elimination of sulphur is affected by such factors as the concentration of lime, its form, the basicity of sinter mix and, in particular, its carbon content, over which a sinter-plant operator has some measure of control.

CONCLUSIONS

(1) The elimination of sulphur from a sinter mix proceeds in three main stages: oxidation of pyrites with the evolution of sulphur dioxide, absorption of sulphur dioxide by lime with the formation of calcium sulphate, and decomposition of calcium sulphate. These stages do not proceed successively but overlap and at higher temperatures may proceed simultaneously.

(2) With the high heating rates met in practice, the evaporation of moisture and the evolution of combined water is so energetic that ore lumps may be fissured. This disruptive activity of water may materially improve the desulphurization process by exposing pyrites particles to oxidation.

(3) The amount of sulphur transformed into calcium sulphate in the reaction zone of a sinter mix depends mainly on the concentration of lime, its form, and the amount of carbon present.

(4) The formation of a liquid phase increases the rate of sulphur evolution, so that mixes containing more lime may lose sulphur faster than those with smaller lime concentrations, provided that they produce a liquid phase at a lower temperature, but with excessive slagging more sulphur may be trapped in slag envelopes.

(5) Small variations in the lime/silica ratio (0·75–1·25) have little influence on the removal of sulphur during sintering.

(6) In view of the predominant importance of the thermal decomposition of sulphate, the velocity of which sharply increases with increasing temperature (particularly at the reduced oxygen pressure which accompanies the passage of the flame front through the sinter bed), it can be expected that when high temperatures are developed during sintering the influence of lime concentration and the lime/silica ratio will be smaller.

(7) There is an optimum carbon content of a mix at which the rate of sulphur evolution is highest. This depends on sintering conditions and must be determined for each individual case.

(8) Theoretical considerations suggest that when lime is added to sinter mixes to improve their sintering properties, it would be preferable to mix the lime with the ore before the coke addition is made.

(9) Magnesium oxide has no apparent influence on the removal of sulphur during sintering; thus whenever possible the replacement of limestone by dolomite should be beneficial.

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References

1. G. M. Schwab and J. Philinis: *J. Amer. Chem. Soc.*, 1947, vol. 69, pp. 2588–2596.
2. F. R. Milliken: *Mining and Metallurgy*, 1937, vol. 18, pp. 279–282.
3. C. H. Butcher: *Chem. Age*, 1939, vol. 41, pp. 411–413.
4. F. O. Wienert: *Chem. Eng. Min. Rev.*, 1952, vol. 44, pp. 255–260.
5. V. F. Postnikov and I. P. Kirillov: *Zhurnal Khimicheskoi Promyshlennosti*, 1934, no. 9, pp. 51–54.
6. F. C. Thompson and N. Tilling: *Journal of the Society of Chemical Industry*, 1924, vol. 43, pp. 37T–46T.
7. H. K. Work and F. M. Hamilton: *Amer. Inst. Min. Met. Eng., Blast Furn. Raw Mat. Comm.*, 1946, vol. 5, pp. 85–92.
8. K. M. Malin: *Zhurnal Khimicheskoi Promyshlennosti*, 1954, no. 7, pp. 1–3.
9. F. D. Richardson and C. J. B. Fincham: *J. Iron Steel Inst.*, 1954, vol. 178, pp. 4–15.
10. S. N. Ganz: *Zhur. Priklad. Khim.*, 1953, no. 5, pp. 464–474.
11. W. L. Bedwell: "The Production of Sulphuric Acid from Calcium Sulphate," Lectures, Monographs, and Reports Series No. 3: 1952, London, Royal Institute of Chemistry.
12. G. Marchal: *J. Chim. Phys.*, 1925, vol. 22, pp. 325–348, 413–431, 559–582; 1926, vol. 23, p. 38.
13. J. Zawadski: *Zeitschrift für anorganische und allgemeine Chemie*, 1932, vol. 205, pp. 180–190.
14. K. K. Kelley: *U.S. Bur. Mines, Bull.* 406, 1937.
15. D. Joyce: *J. Iron Steel Inst.*, 1948, vol. 159, pp. 291–296.
16. C.-G. Thibaut and J. Astier: "Essais de désulfuration et passage au haut fourneau de minerai barytique de Khenifra," ser. A, no. 83: 1954, St. Germain-en-Laye, IRSID.
17. F. D. Richardson, J. H. E. Jeffes, and G. Withers: *J. Iron Steel Inst.*, 1950, vol. 166, pp. 213–235.
18. H. O. Hofman and W. O. Mostowitsch: *Trans. Amer. Inst. Min. Met. Eng.*, 1908, vol. 39, pp. 628–653.
19. B. Neumann: *Zeitschrift für angewandte Chemie*, 1926, vol. 39, pp. 1537–1542.
20. R. Wild: Private communication.
21. J. Konarzewski: *Rocznik Chemji*, 1931, vol. 11, pp. 516–528, 607–635.
22. E. M. McBriar *et al.*: *J. Iron Steel Inst.*, 1954, vol. 177, p. 321.
23. P. K. Gledhill, G. C. Carter, and C. F. Ely: *Ibid.*, 1953, vol. 175, pp. 277–279.

Rate of Desulphurization of Carbon-Saturated Iron by Blast-Furnace Slags

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SYNOPSIS

Following laboratory experiments in which it was shown that large degrees of agitation do not produce equivalent increases in the rate of desulphurization of liquid iron by blast-furnace slags, a theoretical investigation of the kinetics has been made. It is concluded that the desulphurization could be intrinsically slow as a consequence of low steric factors. 1066

THE DIFFICULTIES of removing metalloids during the production of steel have grown markedly during the last few years. As a consequence of inferior coal, leaner ores, and the conversion of many furnaces to oil-firing, there has been a general increase in metalloids associated with each ton of steel manufactured. Recent reductions in scrap availability have aggravated the situation and there is an ever-increasing demand for blast-furnace metal low in sulphur, silicon, and phosphorus. Of these impurities, sulphur is probably the easiest to remove and for many years it has been customary at some plants to treat the hot metal leaving the blast-furnace with soda ash, thereby eliminating as much as 80% of the sulphur. Unfortunately, the use of soda slags can result in considerable damage to furnace refractories; although this treatment is performed in a ladle, it is difficult to skim the last traces of the soda slag[1] from the surface of the metal and thus soda ash enters the mixer or open-hearth furnace, with consequent damage to the banks, roof, and checkers.

Several suggestions have been made for desulphurizing hot metal and at the same time avoiding the use of soda ash. Most of these are concerned with the use of high-melting-point materials such as calcium carbide or mixtures of quicklime and coke breeze, as in the Kalling process, yielding clinkers rather than slags. Unfortunately these processes are marred by the presence of traces of blast-furnace slag, and this fact caused B.I.S.R.A. to investigate possible means of desulphurizing blast-furnace metal with suitable liquid slags not containing sodium. Blast-furnace slag itself could conceivably be used for this purpose since it is often capable of extracting more sulphur from the iron than it does within the blast-furnace, as shown by Filer and Darken.[2] Moreover it could, in principle, be made a more potent desulphurizer by a preliminary blowing with air in the absence of metallic iron, such a treatment eliminating much of the sulphur without appreciably increasing the oxygen capacity of the slag. This process of desulphurization is attractive because of the large quantities of molten blast-furnace slag available during iron production in the U.K.

The first B.I.S.R.A. hot-metal desulphurizing experiments have therefore been conducted with carbon-saturated iron containing sulphur and synthetic blast-furnace-type slags. It is known from practical experience of the blast-furnace and from laboratory experiments, such as those of Hatch and Chipman,[3] that such slags, although far from basic, can produce a large measure of desulphurization because of their low oxygen potential. The experiments were designed therefore, not to study equilibrium conditions but to investigate the variables affecting the rate of desulphurization. It is obviously important that this shall be as high as possible.

It has been quite definitely established,[4, 5] using experimental melts ranging in weights from several grammes to several pounds, that agitation of the slag and metal produces a marked increase in the rate of desulphurization. Unfortunately it has not been possible to measure 'agitation' quantitatively and consequently the effect of the 'degree of agitation' on the rate of desulphurization is still very much in doubt. Several experiments have been made using approximately 7·5 lb. of carbon-saturated iron initially containing approx. 0·3% of sulphur and approx. 2·5 lb. of slag (CaO, 40%; SiO_2, 40%; Al_2O_3, 20%) at temperatures of about 1450° C. In some cases agitation has been accomplished by cascading the slag and metal together backwards and forwards over a carbon wedge in a carbon-lined cylindrical furnace.[6] In others, nitrogen gas has been blown into the slag–metal mixture using silica and carbon lances; both low (approx. 15 lb./sq. in.) and high (35 lb./sq. in.) pressure gas has been used on different occasions. It is reasonable to suppose that these techniques produced different degrees of slag–metal mixing; for example, high-pressure nitrogen blowing would be expected to produce a greater degree of agitation than low-pressure blowing (this was definitely so when the technique was originally tested using a water model). All this work has given a rather surprising result, viz. that no matter what technique is used for agitation, the rate of desulphurization at any particular sulphur level is approximately constant. The experiments show that agitation produces an increased rate

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of sulphur removal relative to melts made under quiescent conditions, but that the quantity or quality of the agitation appears to be of minor importance.

Intrinsic chemical reactions at ironmaking and steelmaking temperatures are alleged to be extremely rapid in view of the estimated low energies of activation of the reacting molecules (25–75 kcal./mole)[7] and the fact that they are often apparently slow (i.e. have high overall energies of activation) is attributed to the low diffusivities of the reacting substances. In the case of heterogeneous reactions, the rates are also limited by the available interfacial areas and if the formation of additional phases occurs, as for example in the production of bubbles of CO, by the numbers of nuclei present.

The desulphurization reaction can be considered as the substitution of oxygen in the slag by sulphur from the metal, the former combining with carbon atoms to form carbon monoxide, thus*:

$$[S] + (O) \rightarrow (S) + [O] \quad \text{(i)}$$
$$[O] + C \rightarrow CO \quad \text{(ii)}$$

It is well known that reactions in liquids resulting in gaseous products can be sluggish and not markedly affected by agitation, since they are limited by the number of bubble-forming nuclei present. However, it is obviously of interest to establish whether any grounds exist for assuming that reaction (i) is relatively slow. The following theoretical investigation concentrates on reaction (i) only and assumes that reaction (ii) has no influence.

CALCULATION OF DESULPHURIZATION RATE USING SIMPLE COLLISION-RATE THEORY

Very little information is available on the number of interatomic collisions that occur across a liquid/liquid phase boundary between the atoms of one phase and those of the other. Such collisions depend on the extent of interpenetration of the phases (i.e. their mutual surface solubilities), and attempts at studying the kinetics of such systems have been confined to diffusion-layer theories of the Nernst type. The present theoretical investigation has therefore been confined to a homogeneous system in which the slag and metal are considered to exhibit complete mutual solubility. Such a hypothesis avoids the difficulty of assessing interfacial collisions and, it should be noted, assumes complete mixing of the phases as far as interfacial area is concerned.

It is fully appreciated that this hypothesis involving a single-phase system cannot represent conditions existing in one containing two phases, which obviously involves diffusion processes, etc. It is felt, however, that reaction (i) would occur more rapidly in the hypothetical one-phase system, and that if it can be shown that reaction (i) may be slow under these conditions it would be even slower in practice where migration across an interface of limited area takes place.

The assumptions that have been made are as follows:

(1) The desulphurization reaction has the following mechanism

$$[S] + (O) = [O] + (S).$$

The reaction is homogeneous, and the sulphur and oxygen atoms can exist in two different states, viz, [S], (S) and [O], (O).

(2) The solution consists of independent atoms of Fe, C, [O], (O), [S], (S), Ca, Si, and Al.

(3) The total number of atoms within the system remains constant, i.e.

(*a*) [S] atoms + (S) atoms = constant
(*b*) The drop in number of (O) atoms required for desulphurization is *instantaneously* neutralized by the introduction of fresh (O) to the system so that the number of (O) atoms is constant. (Actually if the (O) atoms were permitted to decrease, i.e. by making no extra (O) additions, the effect on the calculation would be negligible)
(*c*) The numbers of [O] and C atoms remain constant. Thus as desulphurization proceeds the extra numbers of [O] atoms are removed from the system *instantaneously* as CO by the addition of new C atoms
(*d*) The numbers of Fe, Ca, Si, and Al atoms remain constant. These act merely as diluents.

The reduction of any slag–metal system to the above hypothesis should yield theoretical desulphurization rates higher than those found in practice, other things being equal. Thus the assumption of complete mutual solubility between metal and slag considerably increases the total number of interatomic collisions occurring in unit time and hence the rate of chemical reaction relative to that obtained in practice where only collisions at an interface would be effective. The assumption that all the oxygen atoms (with the exception of [O] atoms, which are relatively few anyway) have equal chances of reacting with the ' metal ' sulphur will also cause the theoretical rates to be higher than in practice, since it is known that many of the oxygen atoms in silicate slags (particularly acid slags) are bound into a silicon–oxygen network and are in this way considerably hindered in their reactivity with sulphur. High theoretical rates will also result from assumptions (*b*) and (*c*); in fact, the only tendency that the hypothetical solution has to slower reaction rates is that caused by the decreases in *concentrations* of the various substances arising from them being considered as distributed evenly throughout one phase instead of the usual slag and metal phases. However, this effect is expected to be of a much lower order of magnitude than the others already mentioned, and thus it is reasonably certain that the reaction rates of the hypothetical solution will be higher than those of its practical counterpart. If, therefore, the desulphurization rate of the former is found to be low, it can reasonably be assumed that the practical reaction rate (i) will be low; in this case the degree of agitation will not have a marked effect on the overall desulphurization rate.

The calculation has been performed on the following practical system, since this has been used in most of the desulphurization experiments so far performed:

Temperature, 1450° C. (1723° K.)

Metal	7·625 lb.	Initial composition	4% C
			0·3% S
			0·002% O
Slag	2·625 lb.	Initial composition	40·0% CaO
			40·0% SiO_2
			20·0% Al_2O_3

* Atoms associated with iron and slag are given square and round brackets, respectively.

Then 100 g. of homogeneous solution contains:

Fe	71·2 g.
C	2·98 g.
[O]	0·0015 g.
[S] + (S)	0·223 g.
CaO	10·24 g.
SiO_2	10·24 g.
Al_2O_3	5·12 g.

	Gramme atoms	Atom Fraction
Fe	1·272	0·479
C	0·248	0·092
[O]	0·0000937	0·0000353
[S] + (S)	0·00697	0·00263
(O)	0·676	0·255
Ca	0·183	0·069
Si	0·171	0·0644
Al	0·101	0·0381
Total	2·658	1·00017

Ionic diameters of O^{2-} and S^{2-} are $2·8 \times 10^{-8}$ cm. and $3·68 \times 10^{-8}$ cm., respectively. These are assumed to be the effective collision diameters of (O), [O] and [S], (S). Thus, the average diameter for S and O is $3·24 \times 10^{-8}$ cm.

If $[S]_0$ represents the *weight percentage* of 'metal' sulphur in the homogeneous solution at any instant, the atom fraction of 'metal' sulphur is given by

$$\frac{[S]_0}{32 \times 2·658} = 0·01179\ [S]_0$$

The density of the homogeneous solution is found by assuming that the metal and slag dissolve in one another ideally, i.e. without any net volume change. The density of the molten iron phase is 7·5 g./c.c. and that of the slag phase is 3·0 g./c.c.

Hence the average density of homogeneous solution is

$$\frac{100}{\frac{74·4}{7·5} + \frac{25·6}{3·0}} = 5·42 \text{ g./c.c.}$$

The net rate of desulphurization is the difference between two opposing reactions, viz. a forward desulphurizing reaction involving interaction between [S] and (O) and a back resulphurizing reaction involving interaction between (S) and [O]. The forward reaction will be considered first.

It is necessary to calculate the total number of collisions between [S] and (O) atoms that occur per cubic centimetre of solution per second. An approximate value can be obtained by assuming that the solution behaves as an ideal gas, i.e. that the total number of collisions per cubic centimetre per second is the same as would be obtained if an ideal gas at the same temperature and composition were compressed to give the same number of atoms or molecules per cubic centimetre. The formula for the total number of collisions per cubic centimetre per second between two components A and B in such a system is given by[8]:

$$N_A N_B \sigma^2_{AB} \left[8\pi RT \left(\frac{1}{M_A} + \frac{1}{M_B} \right) \right]^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots (1)$$

where N_A, N_B are the number of atoms per c.c. of A and B, respectively
σ_{AB} is the mean collision diameter of A and B
M_A, M_B are the molecular (atomic) weights of A and B, respectively.

In the present case 100 g. of solution occupies 100/5·42 c.c. and contains 2·658 g. atoms. Hence the number of g. atoms per c.c. = 0·144, and consequently the number of (O) atoms per c.c. $= 2·24 \times 10^{22}$. Similarly, [S] atoms per c.c. $= 1·034\ [S]_0 \times 10^{21}$.

From formula (1), total number of [S] — (O) collisions per c.c. per sec. $= 1·414[S]_0 \times 10^{34}$. The number of atoms of [S] that change to (S) per second due to the forward reaction equals the number of effective [S] — (O) collisions; i.e.

$$\text{Reduction of [S] atoms per c.c. per sec. (forward reaction only)} = 1·414 \times 10^{34}[S]_0 P_1 e^{-E_1/RT} \quad \ldots\ldots\ldots\ldots (2)$$

where E_1 is the energy of activation and P_1 the steric factor.

The back reaction (involving [O] and (S) atoms) can be treated similarly thus:

$$\text{Formation of [S] atoms per c.c. per sec. (back reaction)} = 1·659 \times 10^{32}(0·00263 - 0·01179[S]_0) P_2 e^{-E_2/RT} \quad \ldots (3)$$

where E_2 and P_2 are the energy of activation and steric factor, respectively, for the back reaction.

Hence the net reduction of 'metal' sulphur atoms is given by the difference between equations (2) and (3):

$$\text{Number of 'metal' sulphur atoms per c.c. } (\underline{S}) = 1·034 \times 10^{21}[S]_0$$

Hence rate of decrease of $\underline{S}$ with time (sec.) is given by

$$-\frac{\partial \underline{S}}{\partial t} = -1·034 \times 10^{21} \frac{\partial [S]_0}{\partial t} = RHS(2) - RHS(3)$$

This simplifies to

$$-\frac{\partial [S]_0}{\partial t} = A[S]_0 - B \quad \ldots\ldots\ldots\ldots (4)$$

where $A = 1·363 \times 10^{13} P_1 e^{-E_1/RT} + 1·89 \times 10^9 P_2 e^{-E_2/RT}$

and $B = 4·22 \times 10^8 P_2 e^{-E_2/RT}$

Integration of equation (4) gives

$$t = \frac{2·3026}{A} \log_{10} \left(\frac{0·223A - B}{A[S]_0 - B} \right) \quad \ldots\ldots\ldots\ldots (5)$$

Provided that values of A and B can be found (i.e. values for P_1, P_2, E_1, and E_2) the desulphurization which has occurred in any time period t can be calculated.

At equilibrium $A[S]_0 - B = 0$, from equation (4), and if P_1 is assumed to be equal to P_2 (i.e. $P_1 = P_2 = P$) and a value is given to E_1, E_2 can be calculated.

It has therefore been assumed that

(*a*) $P_1 = P_2 = P$
(*b*) $[S]_{e(equil.)} = 0·0297\%$ (based on experimental data)
(*c*) $E_1 = 75{,}000$ cal./mole (according to the literature,[7] values for intrinsic chemical reactions of interest in high-temperature metallurgy are probably within 25–75 kcal./mole)

Equation (5) then becomes

$$t = \frac{4·66 \times 10^{-4}}{P} \log_{10} \frac{11·02 - 1·415}{49·43[S]_0 - 1·415} \quad \ldots\ldots \quad \ldots\ldots (6)$$

From equation (6) and any assumed value for the

steric factor P, the amount of desulphurization that has occurred after any time interval can be calculated.

Figure 1 shows two such curves which have been drawn for P values of 10^{-6} and 10^{-7}. The sulphur values are those obtained from equation (6) after multiplying by 100/74·4, i.e. the $[S]_0$ concentrations are adjusted to the values which would be obtained if the 'metal' sulphur were confined to the metal phase only, as occurs in practice. Figure 1 also includes the curve from data obtained from a nitrogen blowing experiment (low pressure). It is apparent that a value of P (between 10^{-6} and 10^{-7}) could be chosen which would give theoretical desulphurization rates very close to those obtained in practice. The broken-line curve in Fig. 1 shows the theoretical rate of desulphurization obtained when there is no back reaction, i.e. when any slag sulphur is incapable of reverting back to the metal. The influence of the back reaction is seen to be small down to [S%] $\simeq 0{\cdot}1$. As equilibrium concentrations are approached the influence obviously becomes more important until finally it is the overriding factor.

Since P values of 10^{-6} or 10^{-7} produce theoretical rates of desulphurization similar to those obtained in practice and since, as already pointed out, the theoretical rates (i.e. using the homogeneous solution concept) are probably higher than their practical counterparts, there seems no *theoretical* justification for stating that the overall practical rates must be limited by other factors, such as diffusion or bubble formation. In other words, provided that P values of 10^{-6} or 10^{-7} are permissible, it is possible that the intrinsic desulphurization reaction (in the particular slag–metal system studied) is slow and that the desulphurization rate is not greatly influenced by the degree of agitation (as found in practice). In kinetic studies P values as low as 10^{-8} have been recorded,[8] although the molecules involved in the reactions were somewhat complex.

The above hypothesis has assumed that all the atoms O, Si, etc., are free to perform collisions as if the system behaved as an ideal gas. It is much more likely that most of the silicon and oxygen atoms within the slag are held together as an interpenetrating network and although there is no long-range order, many of the oxygen atoms may only be replaceable by sulphur atoms if they are impacted in *particular* directions, i.e. for low values of P. In this connection it is interesting to note that the rate problem could have been investigated on the assumptions that effective collisions for desulphurization are those between 'metal' sulphur atoms and silicon–aluminium–oxygen chains, there being no free oxygen atoms. The difficulty of such a treatment is the assessment of the average collision diameter of the chains or network, since the silicon–aluminium–oxygen groups are not separate entities but are continually disintegrating and reforming. However, to make this method of approach clear, the following calculation has been made on a slag containing 50% CaO and 50% SiO_2 with a small amount of sulphur. It has been assumed that all the oxygen atoms are linked to silicon atoms as open chains. This being so, each chain is found to have on an average 14·0 silicon atoms and 43·0 oxygen atoms, and each of these

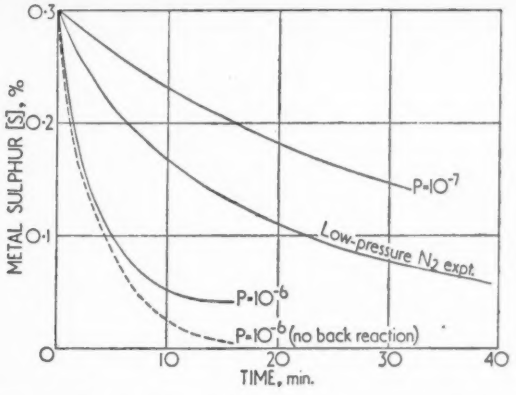

Fig. 1—Comparison of [S%] *v.* time curves obtained theoretically and by the low-pressure nitrogen blowing experiment

chains is considered to behave as a free molecule capable of taking part in a collision. Although the overall length of a silicon–oxygen chain is less than the sum of the silicon–oxygen distances (each assumed to be $1{\cdot}55 \times 10^{-8}$ cm.), owing to bond angles being less than 180°, it has here been assumed that the the chains are linear. Thus:

$$\begin{aligned}\text{Chain length} &= 1{\cdot}55 \times 10^{-8} \times 14{\cdot}0 \times 2\\ &= 43{\cdot}4 \times 10^{-8}\ \text{cm.}\\ \text{Chain width} &= 1{\cdot}55 \times 10^{-8} \times 2\\ &= 3{\cdot}10 \times 10^{-8}\ \text{cm.}\end{aligned}$$

It is sufficiently accurate to assume that the average diameter of each chain is given by

$$\frac{(2 \times 3{\cdot}1 + 43{\cdot}4) \times 10^{-8}}{3} = 16{\cdot}53 \times 10^{-8}\text{cm.}$$

If d represents the density of the CaO–SiO_2–S system,

No. of S atoms per c.c. $= N_S$

No. of chain molecules per c.c.

$$= \frac{0{\cdot}0595d}{100} \times 6{\cdot}1 \times 10^{23}$$

Average molecular weight of chains = 1080

$$\text{Average collision diameter} = \frac{(16{\cdot}53 + 3{\cdot}68) \times 10^{-8}}{2} = 10{\cdot}11 \times 10^{-8}\ \text{cm.}$$

By substituting in equation (1), the number of sulphur-atom/chain collisions per cubic centimetre per second is given by

$$6{\cdot}66 \times 10^{5} N_S d(8\pi RT)^{\frac{1}{2}}$$

If now the previous hypothesis is used (viz. in which the slag consists of independent atoms of Ca, O, S, Si) the number of sulphur/oxygen collisions per cubic centimetre per second is given by

$$5{\cdot}15 \times 10^{4} N_S d(8\pi RT)^{\frac{1}{2}}$$

It is seen, therefore, that the number of sulphur/silicon–oxygen chain collisions per cubic centimetre per second is less (approx. 7·5 times less) than the sulphur/oxygen collisions per cubic centimetre per second obtained using the independent atom hypothesis. Moreover, it is reasonable to suppose that P

will be considerably less than unity for the former theory, since many of the collisions between the chains and sulphur atoms will be ineffective, not because of inadequate activation energies but because the collisions have involved impacts with parts of the chains unfavourable for reaction with oxygen. The chain hypothesis applied to the alumina slags would thus yield slower desulphurization rates than those obtained with the independent atom theory because the number of collisions per second involving sulphur would be less and also because P would be lower (assuming similar activation energies).

It is generally concluded that the value of P is of great significance and values of about 10^{-6} can result in desulphurization rates being slow even when their activation energies are low (25–75 kcal./mole). For some reactions, values of P as low as 10^{-8} have been recorded.[8] Thus, unless it can be established that P values for slag systems such as those studied above are much greater than approx. 10^{-6}, it is possible that certain slag–metal chemical reactions are inherently slow.

GENERAL CONCLUSIONS

Using a purely theoretical approach, there is no *a priori* justification for the statement that slag–metal desulphurization reactions are intrinsically extremely rapid. Confining the calculation to a homogeneous reaction and assessing reasonable activation energies to the forward and backward reactions, the overall desulphurization is found to be strongly dependent upon the choice of steric factor values. Using steric factors of 10^{-6} or 10^{-7} (values as low as 10^{-8} have been found for some reactions[8]), the theoretical desulphurization rates can be brought within those observed in nitrogen blowing and rocking experiments. It may be argued that the steric factors would be much nearer to unity than, say, 10^{-6} because the desulphurization reaction is to a certain extent ionic. However, this must await experimental verification.

An alternative theoretical approach is presented which involves the concept of desulphurization occurring as a result of the interaction of sulphur atoms and silicon–oxygen–aluminium chains. It is shown that such an approach would result in even slower rates of desulphurization than those obtained initially, i.e. when all the atoms in the system are assumed to behave with complete freedom.

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References

1. A. H. Leckie, C. E. A. Shanahan, and F. J. Lund: *J. Iron Steel Inst.*, 1953, vol. 175, p. 51.
2. E. W. Filer and L. S. Darken: *Trans. Amer. Inst. Min. Met. Eng.*, 1952, vol. 194, pp. 253–257; *J. Met.*, 1952, vol. 4, Mar.
3. G. G. Hatch and J. Chipman: *Trans. Amer. Inst. Min. Met. Eng.*, 1949, vol. 185, pp. 274–284; *J. Met.*, 1949, vol. 1, Apr.
4. C. E. A. Shanahan: *Metallurgia*, 1952, vol. 45, pp. 59–61.
5. C. E. A. Shanahan: *Metal Treatment*, 1953, vol. 20, pp. 517–520.
6. C. E. A. Shanahan and F. J. Lund: *Iron Coal Trades Rev.*, 1953, vol. 166, pp. 701–705.
7. C. F. Goodeve: *Disc. Faraday Soc.*, 1948, No. 4, pp. 9–23.
8. C. N. Hinshelwood: "The Kinetics of Physical Change": Oxford University Press.

The Role of Iron-Ore Beneficiation

THE SOLUTION OF THE TACONITE PROBLEM IN THE U.S.A.

By William A. Haven

SYNOPSIS

Exhaustion of high-grade iron ores from the Lake Superior ranges in the foreseeable future has focused attention on the possibility of supplementing the remaining supply of these with ore derived from the enormous bodies of taconite, the hard ferruginous rock from which the rich Mesabi deposits were formed. To accomplish this, unusual difficulties in mining, concentration, and especially agglomeration were involved. The paper draws attention to the increasingly important role of iron-ore beneficiation in the manufacture of pig iron and deals more specifically with the development of new agglomerating processes that have helped to solve the taconite problem. 1108

Introduction

THE BLAST-FURNACES in the north-central part of the U.S.A. that have been dependent upon the soft, rich, and easily mined iron ores of the Lake Superior region account for the production of about 50 million net tons of pig iron annually, or about two-thirds of the total for the country. Iron and steelmaking plants and industries serving, served by, or otherwise associated with iron and steelmaking, represent a capital investment of billions of dollars and provide a livelihood for millions of people. During World War II the annual consumption of Mesabi and other high-grade Lake ores reached almost 100 million tons, whilst officially reported reserves amounted to little more than 1,000,000,000 tons. Actual reserves of good-grade and marginal ores may have been twice this amount but, even so, the recovery of more ore from the low-grade deposits in the same area had

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Table I

SHIPMENTS FROM UPPER LAKE PORTS AND ALL-RAIL FROM MINES (U.S.A. AND CANADA)

In thousands of gross tons (upper railway weights)

(From Lake Superior Iron Ore Association)

Year	Total	Year	Total
1885	2,468	1942	93,487
1890	9,011	1943	86,421
1895	10,441	1944	82,354
1900	19,102	1945	76,981
1905	34,405	1946	61,013
1910	43,440	1947	79,704
1915	47,266	1948	84,690
1920	60,417	1949	70,987
1925	55,518	1950	82,178
1930	47,185	1951	97,011
1935	28,504	1952	80,435
1940	64,309	1953	99,025
1941	81,210	1954	62,258

Grand total, 1884–1954, 2,967,096,000 gross tons

become a matter of great importance to the national economy. Consequently, during the past ten years there have been renewed and intensified efforts to recover in usable form the several billion tons of iron-bearing minerals contained in the parent iron-bearing rock of the Lake Superior formations, known as taconite (*see* Tables I and II).

In scientific terms, "The essential minerals of taconite are quartz (chert if texture is to be emphasized), silicates as a group, magnetite, siderite and other carbonates, and hematite. The arrangement also indicates the order of their abundance. . . . These minerals are combined in all conceivable proportions and depending upon these and their textures we have cherty taconites, carbonate taconites, magnetic taconite, jaspery and hematitic taconites, banded and slatey taconite" (Gruner[1]). For legal purposes taconite is defined in the laws of Minnesota as "ferruginous chert or ferruginous slate in the form of compact, siliceous rock, in which the iron oxide is so finely disseminated that substantially all of the iron-bearing particles of merchantable grade are smaller than 20 mesh," and further as "ore-bearing rock which is not merchantable as iron ore in its natural state, and which cannot be made merchantable by

Table II

IRON ORE PRODUCED IN THE U.S.A., 1953

By state and type of product, in gross tons (exclusive of ore containing 5% or more of manganese)

Taken from *Skilling's Mining Review*, 16th October, 1954

State	Direct Shipping Ore	Sinter*	Concentrates	Total	Iron Content (Natural), %
Mined Ore:					
Alabama	4,451,288	1,092,173	1,918,918	7,462,379	37·97
Arkansas	254	...	...	254	58·66
California	1,627,357	...	...	1,627,357	53·64
Colorado	900	...	...	900	48·50
Georgia	28,982	...	181,682	210,664	43·48
Michigan	13,613,535	...	199,806	13,813,341	50·96
Minnesota	54,430,622	1,121,052	24,533,940	80,085,614	50·31
Missouri	...	...	274,693	274,693	53·59
Montana	6,709	...	...	6,709	50·01
Nevada	426,753	...	...	426,753	63·11
New Jersey	236,034	...	640,134	876,168	61·82
New Mexico	7,525	...	...	7,525	56·33
New York	76,682	2,899,888	287,803	3,264,373	62·75
Pennsylvania	...	778,561	242,711	1,021,272	57·51
South Dakota	1,060	...	...	1,060	38·00
Tennessee†	5,951	...	12,751	18,702	34·00
Texas	...	160,123	869,204	1,029,327	47·68
Utah	4,838,983	...	...	4,838,983	54·15
Virginia†	...	...	...	...	..
Wisconsin	1,756,150	...	...	1,756,150	53·04
Wyoming	655,097	...	...	655,097	49·96
Total ore mined	82,163,882	6,051,797	29,161,642	117,377,321	50·36
***By-Product Ore*‡** Delaware, Tennessee, Virginia	...	617,448	...	617,448	65·91
Grand Total	82,163,882	6,669,245	29,161,642	117,994,769	50·44

(Sintering capacity at blast-furnace plants in U.S.A. = approximately 25,000,000 tons.)

* Exclusive of sinter produced at consuming plants.
† Small tonnage mined in Virginia included with Tennessee.
‡ Cinder and sinter obtained from pyrites treated in, but not necessarily mined in, states indicated.

simple methods of beneficiation involving only crushing, screening, washing, jigging, drying or any combination thereof."

From these definitions and the fact that the rock, in place, is massive and extremely hard, it can be realized that to mine the taconites, as well as to concentrate and agglomerate the extremely fine iron-bearing particles, would be unusually difficult. Grinding to 150 mesh, with 85% through 325 mesh, is required before the constituent minerals can be effectively separated. Initial attempts at concentration, therefore, have been directed principally at the magnetic taconites, to which the easiest and cheapest methods can be applied. It is conservatively estimated that about 1,700,000,000 long tons of magnetic taconite concentrates can be had from open-pit mines on the Mesabi range alone (estimated reserves of taconites and chemical analyses are given in Table III).

The idea of using the Lake Superior taconites was conceived many years ago and was tried out on a large scale in the early 1920's. This attempt to solve the problems involved was not carried very far, principally because the ample supply and comparatively low price of high-grade iron ore at that time would not warrant the cost of mining, concentrating, and agglomerating such lean and refractory material. In the intervening years, however, the base price of Lake Superior ore at lower lake ports had risen from \$5.55 to \$9.90 per ton, or, from 10·8 cents to 19·2 cents per unit of iron content. From \$25.00 to \$30.00 per ton has been paid in some cases to import high-grade ores that have been in short supply for basic open-hearth steelmaking. The value of iron ore at the furnaces has now become so high as to indicate profit potentialities in utilizing low-grade ores that did not exist in 1920. Meanwhile, also, practically all the methods, machines, and know-how

Table III

ESTIMATES OF RESERVES AND ANALYSES OF TACONITE

(*a*) Minnesota Taconite Estimate

Reserves which can be extracted magnetically (Gruner[4])

Formation	Reserves
Open pit, including East Mesabi Range	5,000,000,000–6,000,000,000
Underground from Lower Cherty division 260 million tons per square mile area: Total for 1 mile width to depths of 800–1500 ft., depending on local dip of formation	21,000,000,000
Additional tonnages from Upper Cherty division for a belt of the same width below zone of alteration	10,000,000,000

(*b*) Probable Analysis of Taconite, Taconite Concentrate, Sinter, and Pellets

(By courtesy of V. D. Johnston, Oglebay, Norton and Company)

	Taconite (25·6% Magnetic Iron)	Taconite Concentrate, %		Sinter, %		Pellets, %	
		Dry	Natural	Dry	Natural	Dry	Natural
Fe (Total)	31·0	64·45	59·294	64·25	63·286	62·68	60·173
Fe (Ferrous)	...	21·95	20·194	23·35	23·000	0·23	0·221
Fe (Ferric)	...	42·50	39·100	40·90	40·287	62·45	59·952
P*	0·04	0·025	0·023	0·023	0·023	0·023	0·022
SiO_2	45·00	8·52	7·838	9·05	8·914	8·28	7·949
Mn	0·60	0·20	0·184	0·22	0·217	0·19	0·182
Al_2O_3	0·70	0·39	0·359	0·42	0·414	0·38	0·365
CaO	3·00	0·56	0·515	0·60	0·591	0·54	0·518
MgO	2·40	0·83	0·764	0·88	0·867	0·81	0·778
S		0·002	0·002	0·013	0·013	0·001	0·001
TiO_2		0·036	0·033	0·036	0·035	0·036	0·035
Cu		0·000	0·000	0·000	0·000	0·000	0·000
Pb		0·000	0·000	0·000	0·000	0·000	0·000
Zn		0·000	0·000	0·000	0·000	0·000	0·000
Co		0·000	0·000	0·000	0·000	0·000	0·000
Ni		0·000	0·000	0·000	0·000	0·000	0·000
Cr		0·000	0·000	0·000	0·000	0·000	0·000
C		0·000	0·000	0·000	0·000	0·000	0·000
Ignition loss, %		0·30	0·276	0·12	0·118	0·03	0·029
Gain on ignition, %		2·86	2·631	3·26	3·211	0·00	0·000
Estimated moisture, %			8·00 (filter cake)		1·50		4·00

* Taconite products are suitable in regard to phosphorus content for either basic open-hearth or acid Bessemer use. Because of their low alumina content, however, high-alumina materials may have to be added to furnace burdens to produce the type of slag desired in U.S. blast-furnace practice.

that are used in the beneficiation of iron ores have been greatly improved and have provided much more effective means of attacking the taconites.

GROWING IMPORTANCE OF IRON-ORE BENEFICIATION

The progress that has been made in converting low-grade or otherwise unsatisfactory iron-bearing minerals into blast-furnace charge materials that can be economically smelted is much greater, and bears a more important relationship to the production of pig iron in almost every iron-producing locality than seems to be realized or appreciated even by many closely associated with the iron and steel manufacturing industries. Perhaps this is because iron-ore beneficiation was not urgently needed until the end of the 19th century, since the first iron-making centres were located in close proximity to supplies of metallurgical fuel and deposits of ore, either rich or poor, that could be smelted at a profit in their natural state. This was the case on the European continent, in the U.K. and in the U.S.A. and the period of profitable operations for such localities was prolonged by the development of cheap means of transportation—rail, water, or a combination of both—which permitted established plants to survive on transported ores after local supplies had been depleted. Thus, U.K. ironworks were able to use the low-grade Lincolnshire ores in lumps as large as could be charged into the furnaces, despite excessive fuel consumption, and U.S. works the Mesabi ores as fine as powder, despite losses of as high as 15% in the form of flue dust. Rising costs and competition put an end to this period and beneficiation of their ores then became essential to the survival of many plants. Rapid progress in improving beneficiation methods and equipment then followed.

Modern methods of iron-ore beneficiation have thus helped to keep some of the older ironmaking establishments in operation. They have also been responsible for increasing the productive capacity of many blast-furnaces beyond what it would have been had it been necessary to continue using the available ores as mined. When the maximum capacity of U.S. blast-furnaces reached 500 net tons daily, about 40 years ago, it was concluded by some that the peak in output for single furnaces had been reached. Mechanical problems and metallurgical theories tended to limit the diameters of the hearths and tops, the size of the bells, and the capacities of the filling equipment, hot-blast stoves, and blowing engines. However, operating and designing engineers demonstrated effectively that these obstacles could be overcome, and there are now furnaces that are capable of producing 1500 tons or more of iron daily from many varieties and grades of iron ores in their natural state. It has been shown, however, that the output of the same furnaces can further be raised from 10% to 20%, depending upon the amenability of the raw ore to improvement by beneficiation. Also, furnaces dependent upon lean or refractory raw ores, or upon those that are otherwise not well suited for smelting, can often, by beneficiation of these materials, be enabled to produce as much iron as other furnaces favoured with ores that are high-grade as they occur.

In this paper the term ' beneficiation ' is intended to include any treatment that will improve the ore for blast-furnace or other metallurgical uses. Generally this means anything that will increase its iron content, make it more reducible, or enable the stock in the furnace to move down more smoothly, continuously, and with less throwing out of flue dust. Improvement in any of these respects that can be accomplished without detrimental effects in other ways will increase the furnace's output of iron, save fuel, reduce losses in flue dust and scrap, and result in a better and more uniform quality of pig iron. The methods of beneficiation commonly used include concentration of the iron content in the ore by screening, roasting, washing, jigging, or magnetic separation; crushing when the ore is massive, hard, or refractory; screening and sizing; blending when there is a wide range in chemical analyses or in particle sizes, before or after crushing; and agglomeration to re-form concentrate or other fines into larger pieces, either light and porous, if for blast-furnace use, or dense and heavy if for open-hearth charging. Frequently more than one form of beneficiation is applied, and in some cases several of them for a single type of ore.

Many instances can be cited to show that without some form of iron-ore beneficiation there are a number of iron-producing plants that could not have been successfully established or could not have survived competition. A number of furnaces in eastern U.S.A. are dependent upon the refractory magnetite ore of New York State, New Jersey, and Pennsylvania. This is one of the oldest iron-producing regions, with furnaces dating back to the 18th century, when anthracite and relatively small surface deposits of hematite and magnetite ores were available as raw materials. Larger deposits of magnetites were later found in these regions but these were deep-seated, very refractory, and mostly low-grade. Many of them might be likened to coarse-grained taconites and it was for these ores that magnetic separation methods found their broad application in the U.S.A. and were developed to a high degree of efficiency. In time, however, the use of cobbed and fine magnetite concentrates become uneconomical because of the large amount of fuel required for smelting them, and would have had to be discontinued had not agglomeration methods been developed to save the situation. Today, these magnetites, concentrated, pulverized, and then sintered, continue to support profitable ironmaking operations in eastern New York and eastern Pennsylvania and occasionally provide fine concentrates for shipment to Buffalo, Cleveland, Youngstown, Pittsburgh, and Baltimore, to improve the quality of sinter made chiefly from softer ore fines and flue dust.

Another district where iron-ore beneficiation has played an outstanding role is in the western part of the U.S.A., at the plants of Pueblo (Colorado), Geneva (Utah), and Fontana (California). Here it is improbable that the coke from Utah coals, almost non-coking, would have been strong enough to permit economical smelting of the hard western ores

had not a combination of beneficiation methods been applied. These consisted of crushing; grading the coarse portions, by screening into several sizes, for separate charging: blending the coarse ores; and sintering a large percentage of the ore represented by the fines. With this extensive preparation of the ore and, in the case of Fontana, some help derived from using 10% of expensive Oklahoma low-volatile coal to improve the strength of the coke, the blast-furnace practice has been made to compare favourably with that in any other area of the U.S.A.

It should be of particular interest to U.K. operators that the combination of beneficiation methods at these western plants was modelled on that used for the first time in 1939 at the Appleby-Frodingham plant of the United Steel Companies Ltd. in Scunthorpe. The keystone in this combination is the blending system where fluctuations in chemical analysis and particle sizes of each grade of ore are practically eliminated. The improvement in furnace output, fuel consumption, and iron quality at Scunthorpe which followed the construction of the South Ironworks is well known. The plant seems to have become a model that is being followed throughout the industry but what may not be appreciated is the fact that the size of the South Ironworks furnaces 9 and 10, although the largest and most modern for that pre-war period, played a secondary role to that of beneficiation in obtaining some remarkable results. The reduction of fuel consumption, now reported to be less than 1900 lb. per gross ton of iron, compared with about 3000 lb. before South Ironworks was built, should be credited mostly to the revolutionary beneficiation plant, complete with crushing, sizing, blending, and sintering facilities.[2]

To the late Sir Robert Hilton, then Director of the United Steel Companies Ltd. and to Mr. William Baxter, at that time Manager of Appleby-Frodingham, belongs the credit for the innovation of satisfactory iron-ore blending. The installation of the Robbins–Messiter system, previously used in copper-smelting operations, was suggested by the present author, but they were the first with the courage to risk the large investment that was needed to apply it to iron-ore blending. Since then, it has been used in the U.K., Germany, and the U.S.A. and has proved to be so valuable in the field of ironmaking that the industry may well accord them a vote of thanks. It is true, however, that in their case the need was unusually urgent because of extremely wide fluctuations in the analysis of Lincolnshire ores and all efforts to blend these ores properly by other methods and with other equipment had failed.

Numerous other cases could be mentioned in which beneficiation of iron ore has been a major, if not the most important, factor in successful ironmaking operations. With the present enhanced value of iron units, many minerals previously considered to be too poor in iron content can now be utilized—fortunately for countries more advanced industrially whose supplies of rich and easily won iron ores are being rapidly exhausted. For example, the ores of east Texas, containing in place only about 15% of iron, are now providing a sound basis for flourishing iron- and steel-producing plants in that part of the U.S.A. Of equal importance, perhaps, is the fact that beneficiation of higher-grade ores is increasing the productive capacity of existing plants and substantially reducing the need for more blast-furnaces. In 1953, of about 150 million tons of ore used in the U.S.A., at least 40% was upgraded by some form of beneficiation. Much of the rich ore now being imported will also require crushing, grading by sizes, and sintering of the fines if it is to be most profitably utilized.

REVIEW OF DEVELOPMENTS IN AGGLOMERATION OF IRON ORES

Technical publications are replete with detailed descriptions of the equipment and methods now used for every form and phase of iron-ore beneficiation. Without being repetitious, the author wishes to review some of the developments that have occurred in agglomeration processes and explain the vital part that these have played in helping to solve the taconite problem. Efforts have been made to sinter taconite concentrates on movable grate machines and nodulize them in rotary kilns, and these efforts are meeting with an increasing amount of success, but only because of improvements that have been made in the design of agglomerating plants as a whole and of the machines and auxiliary facilities.

The early sintering machines were used principally for agglomerating flue dust, great stock piles of which had been accumulated after the comparatively fine Mesabi iron ores became the principal source of raw material for the U.S. blast-furnaces, during the 1890's. The first sintering plants were built about 1910. Characteristic Mesabi ore would contain more than 50% $-\frac{1}{2}$-in. particles and 10–20% −100 mesh. Consequently the flue dust would often be 500 lb. or more per ton of pig iron produced. However, in those days the ore was cheap and the flue dust was generally stocked or wasted. Some operators would recharge considerable amounts of it in the furnaces, but the question of whether or not this was profitable practice was widely debated.

Sintering gradually put an end to the charging of raw dust and rapidly depleted the old stock piles of this material. More and more of the currently produced dust had to be used in the sintering plants and increasing proportions of it in the form of fine wet sludge from tower washers, disintegrators, and precipitators which were being adopted for gas cleaning. The old sintering plants were poorly equipped to handle such materials. Meanwhile, remarkable progress in the design of the furnaces and in stock charging and distributing had greatly reduced the flue-dust losses. Consequently during the 1930's a number of the old sintering plants in the Midwest slowed down or shut down for long periods of time.

Sintering of the eastern magnetite concentrates, however, continued to increase and the greatly improved practice on the eastern furnaces which this brought about was one of the things which directed more attention to the advantages to be gained in sintering the soft Lake ore fines. Another factor in rekindling the interest in sintering these ores was a shortage of lump ore for steelmaking which became a serious problem at the beginning of World

War II, and necessitated screening out the coarser portions of the blast-furnace ores for use in the open-hearths. This procedure increased the percentage of fines in the blast-furnace material and the advantages of sintering these then came to be realized. The building of new, larger, and much better plants began. Basic patents having expired, a wider application of engineering talent to making improvements in the process and equipment naturally followed.

The product from the old plants left much to be desired; in many cases, much of it would be better designated as 'roasted' flue dust. The old plants were lacking in proper equipment for mixing the raw materials (mostly flue dust, coke breeze, and roll scale); for conveying these materials from the bins to the machines and distributing it properly on the machines; for igniting the charge; for maintenance of the machine parts, particularly pallets and grate bars; for screening out, handling, and re-charging the return fines; and for cooling and handling the sinter product. In many cases the arrangement of the various parts of the plants was inefficient. Satisfactory means for avoiding spillage and for dust collecting were lacking and good housekeeping was so much of a problem that a sintering plant was ordinarily considered by the blast-furnace superintendent as 'a good place to keep away from.' Supervision of the sintering plants was generally entrusted to foremen of secondary grade. The application of information developed by research and the use of modern instruments were retarded and control of the operations was difficult.

When the benefits to blast-furnace practice of sintering fine Lake Superior ores began to be realized, strenuous efforts were made, especially by engineering firms interested in building such plants, to correct the deficiencies of the older plants, with marked success in every direction. In modern plants careful sizing, mixing, and conditioning of the charge materials can now be accomplished; conveying, combustion, and mechanical equipment has been greatly improved; better means for screening, cooling, and handling the return fines and sinter product are provided; a multiplicity of instruments are installed to permit accurate control of all operations; and a well managed plant can now be kept as dust-free as is necessary for safe and healthy working conditions. The capacity of individual machines, when working on iron-ore fines, has been stepped up to more than 1800 net tons per day, and plans for individual machines with a daily capacity of more than 4000 tons are being formulated. The annual capacity of sintering plants in the U.S.A. is now more than 30 million tons. The quality of the product, by means of controls that are now provided, has been greatly improved and can be varied, to some extent, to suit the requirements of either the blast-furnace or the open-hearth.

DEVELOPMENT OF METHODS FOR THE AGGLOMERATION OF TACONITE CONCENTRATES

Because of the scepticism with which its agglomerating capabilities were regarded in some quarters, the sintering process was not too widely favoured for treating the extremely fine Minnesota taconite concentrates when these were to be the only iron-bearing part of the charge. The distribution of such fine materials on the grates in a way that would provide a bed sufficiently permeable for satisfactory ignition and combustion was one of the difficulties anticipated. The experience in this phase of the operations gained by experimental test runs was not encouraging. Furthermore, for agglomeration of the finely ground taconites it was believed by some that the fuel costs in the sintering process might be prohibitively high. The quantity of solid fuels ordinarily required to sinter hematite fines amounted to about 7% of the charge by weight, and resulted in a consumption of about 1,800,000 B.t.u. per ton of product. The cost of solid fuels (finely crushed coal or coke breeze) in the Upper Lake regions where the agglomerating plants will be located is about $12 for coal and higher for pulverized coke breeze. Some prejudice against sinter had been created by publication of tests which indicated that sintering hematite ores made them denser and harder to reduce. Nodulizing in rotary kilns, as an alternative to sintering taconite concentrates, whilst not hampered by the problem of permeability, was open to the same objections regarding fuel consumption and quality of product. An additional objection to nodulizing lay in the difficulties that had always been encountered in keeping the kiln temperatures within the very narrow range necessary to accomplish nodulizing on one hand and to avoid melting the charge and thus scaffolding the kiln on the other.

Origin of Pelletizing

These were some of the circumstances that encouraged the consideration of agglomerating by balling or 'pelletizing' the wet concentrates and hardening the pellets by some form of heat-treatment. Research and experimentation along various lines had been conducted for years by Professor E. W. Davis and his associates at the Mines Experiment Station, University of Minnesota, in Minneapolis, and the pelletizing process in their opinion offered the best chance for success on a commercial scale. Several of the iron and steelmaking corporations have extensive holdings of taconites in Minnesota and Michigan and two groups of them, represented by the Reserve Mining Company and the Erie Mining Company, were willing to build pilot-scale plants which became the next necessary step in testing the pelletizing–agglomeration method. Independently, the Oliver Mining Company of the United States Steel Corporation decided to build commercial-scale sintering and nodulizing plants to determine the possibility of using these two methods and their relative merits for agglomerating taconites without pelletizing.[3]

Nodulizing and Sintering Taconite Concentrates

Arthur G. McKee and Company was commissioned to design and build one of the 'pellaglom' pilot plants and also the large-size sintering and nodulizing plants. With the latter, which are combined in one installation at Virginia, Minnesota, after a considerable period of experimentation satisfactory results have been obtained by both processes. The nodules are said to be an excellent feed ore for open-hearth

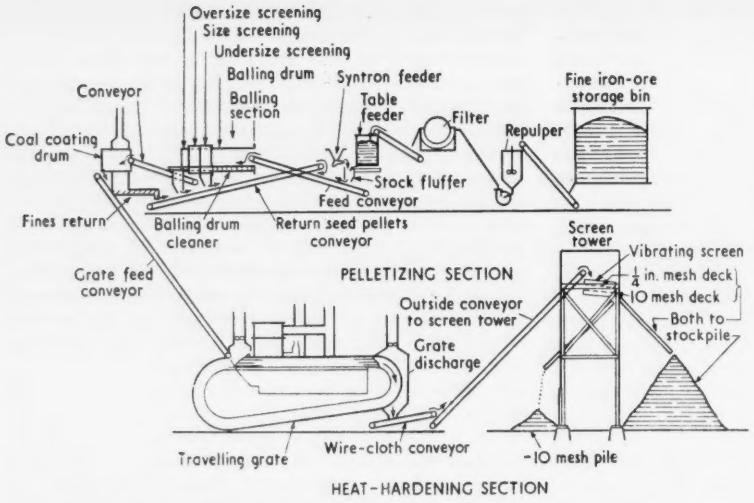

Fig. 1—Carrollville pilot plant: McKee–Allis agglomeration system

furnaces. The sintered product has been found satisfactory for blast-furnace use. There has not yet been a sufficient supply of taconite concentrates to keep these plants operating at full capacity, but the daily rate of production when using these concentrates is about 1100 tons of nodules and 1400 tons of sinter. Fuel consumption is said to be about 1·6 million B.t.u. per ton of nodules and 1·7 million B.t.u. per ton of sinter. The plant was completed in July, 1951. When not processing taconite concentrates it is supplied with hematite fines and has been operated winter and summer since its erection. Evidently agglomeration of taconites by both processes is commercially profitable.[4]

Heat-Hardening Pellets in the Shaft-Furnance

The pellet-agglomerating pilot plant which the McKee Company was commissioned to design and construct was only one of several that have been built to determine the merits of this process. This one, financed and operated by the Reserve Mining Company, was located at Ashland, Kentucky. Taconite concentrates were not then available, so coarser magnetite concentrates from New York State were used as a substitute, after grinding to the fineness that would be necessary when treating taconites. The plant included bins for the storage of concentrates and coal; equipment for pulverizing both materials; a filter for recovering the fine concentrate pulp; controlled feeding mechanism for mixing the fuel and concentrate; a balling drum; a vertical or 'shaft' furnace 4 ft. wide × 2 ft. long × 13 ft. high; and various specially designed equipment for conveying and screening the feed material, for charging and discharging the furnace, and for firing the furnace with natural gas. The plant was well equipped with instruments for measuring the amounts of materials used (including fuel) and temperatures in various parts of the furnace, for enabling the operators to control the various phases of the process, and for recording quantitative and qualitative data. In the original planning, space was provided in the plant for a small sintering machine on which experiments could be made alternatively with the shaft furnace, using the same facilities for preparing and handling the materials, but, mainly in the interest of economy, such provision was omitted.

The Ashland Pilot Plant

The Ashland pilot plant was completed in April, 1949, and experiments were carried on until March, 1952. The theoretical capacity of the shaft furnace was 200 tons daily, and this was reached for short periods of time. A sufficient quantity of hardened pellets was produced to make an experimental run on a small blast-furnace, by which it was found that they were well suited for blast-furnace feed. A large amount of valuable information was acquired about the mechanical difficulties that would be encountered in preparing and handling the raw materials and in making and sizing the raw pellets. None of these appeared to be insurmountable but the operation of the shaft furnace was extremely irregular. This was probably due to fluctuations in the physical stability of the wet raw pellets, slumping of the furnace charge, and consequent formation of clinkers, which made it extremely difficult to discharge the heat-hardened pellets from the furnace. Because of these mechanical and metallurgical difficulties, continuous operation of this plant at full capacity was not accomplished, but the quality of the product and the data acquired in the operations were sufficient encouragement for building, near the mines in Minnesota, a second plant of this type that would have a theoretical capacity of 1000 tons daily.

HEAT-HARDENING PELLETS ON A GRATE-TYPE MACHINE

While this second shaft-furnace plant was being constructed, the McKee Company undertook a further investigation of the possibility of agglomerating the pellets on a horizontal grate-type machine. This was done jointly with the Allis-Chalmers Manufacturing Company, which had acquired certain patent rights for a process that would recover the heat wasted in the ordinary sintering process. The McKee–Allis idea was to design a plant in which the surplus heat from the horizontal-grate machine would be used to condition the raw wet pellets so that they would provide a stable permeable bed of material before and after ignition and also reduce the amount of fuel needed for hardening. The oxidation of magnetites to hematites is an exothermic chemical procedure that will contribute heat to the operations in so far as it occurs.

The Pot-Grate Experiments

The study of heat-hardening pellets by a down-

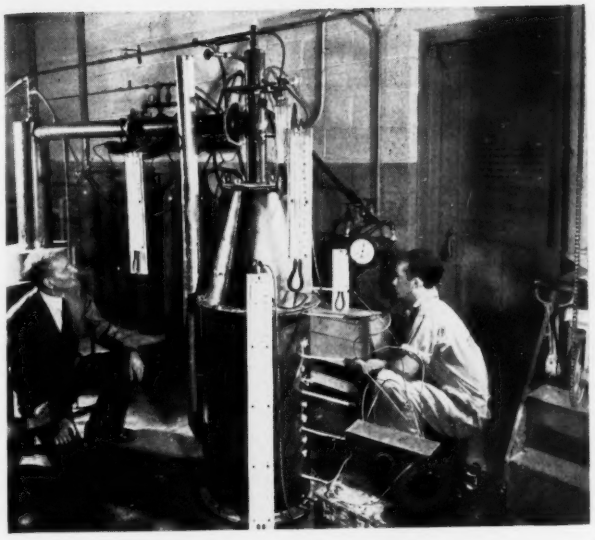

Fig. 2—Pot-grate furnace in laboratory of Allis-Chalmers Manufacturing Company, Milwaukee

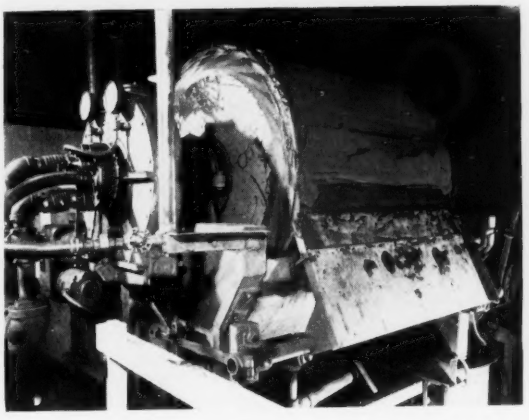

Fig. 3—Filter cake of taconite concentrate from drum filter: Carrolville pilot plant

Fig. 4—Green pellets at discharge end of balling drum: Carrolville pilot plant

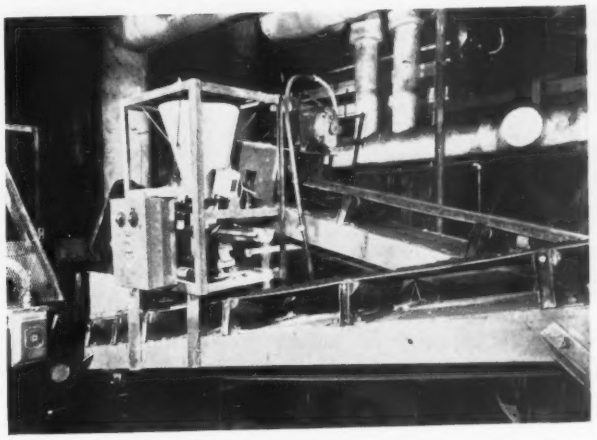

Fig. 5—Concentrate conveyor and bentonite feeder, with seed pellet conveyor in background: Carrolville pilot plant

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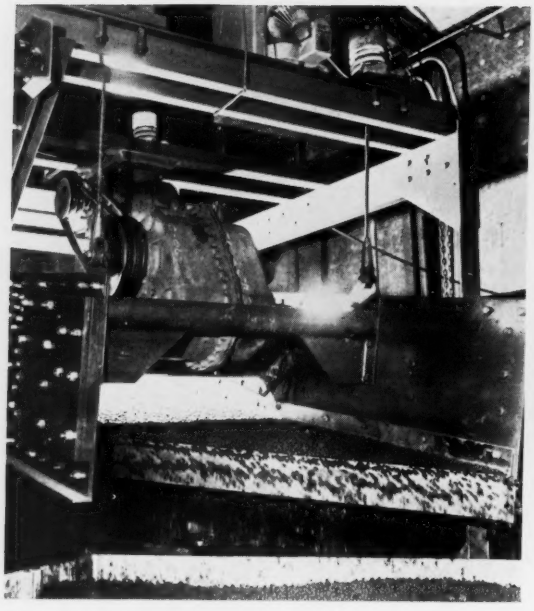


Fig. 6—Green pellets being fed on to travelling grate: Carrolville pilot plant

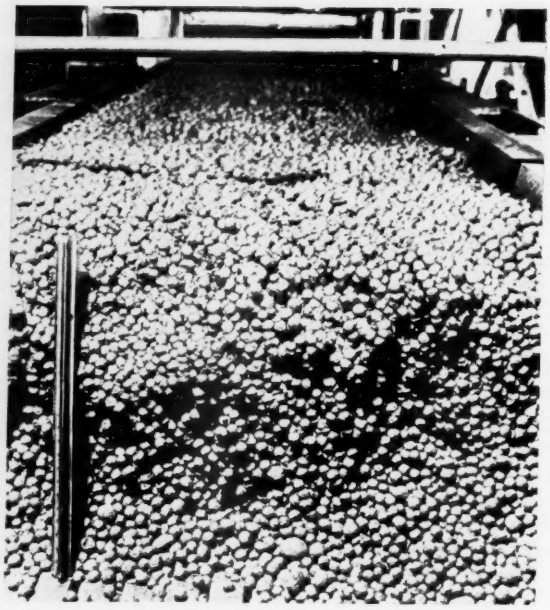


Fig. 7—Heat-hardened pellets at discharge end of travelling grate furnace: Carrolville pilot plant

Fig. 8—Control panel for travelling grate furnace: Carrolville pilot plant

draught process which would utilize sensible heat recovered from the waste gases began with tests in a laboratory furnace or 'pot grate,' but most of the experimental work was done in a pilot plant described below. The pot-grate tests were conducted by Dr. O. G. Lellep, Consultant for the Allis-Chalmers Manufacturing Company of Milwaukee, Wisconsin. The furnace (*see* Fig. 2) consisted of a refractory-lined cylinder of about 12½ in. internal diameter, with a movable grate so that the bed of pellets could be varied in depth from 12 to 20 in. It was equipped with a refractory-lined ignition hood, fuel and air line connections, and instruments as needed to compile the desired data on fuel consumption, air flow, temperatures and pressures, etc.

As initially evolved, the experimental procedure consisted of mixing about 1·0% of finely divided anthracite with magnetite concentrates which contained 9·5–10·0% of moisture, making balls of about ½ in. dia., drying, preheating, and then finally igniting these at about 2350° F. (1287° C.). After their moisture content was reduced to about 6·5% in a small rotary drier, the balls were hand-charged on to the pot grate to a depth of about 14 in. A hearth layer of burned pellets was generally used on the grate but this practice was not adopted for the pilot-plant work. With the hood in place, the charge was given a final drying for about 5 min. at 500° F. (260° C.) before ignition at 2350° F. (1287° C.). The volume of air blown through the charge was gradually increased from 80 cu. ft./min. at the start to about 160 cu. ft./min. toward the end of the experiment, pressure being kept at about 4 in. W.G. Thermocouples inserted into the bed of pellets made it possible to obtain bed temperatures and, ultimately, burning rates for different conditions.

By studying the temperature of the discharged gases for each of the experiments, the amount of sensible heat that would be available for drying and ignition purposes was determined, and it was demonstrated that successful recovery of sensible heat would make the fuel economy of a horizontal-type agglomerating machine fairly close to that of a shaft-type furnace. The product from these experiments was subjected to physical testing and found to be of satisfactory quality for the blast-furnace.

A procedure involving the use of propane gas to extend the required temperatures throughout the bed of pellets was the next development in the pot-grate experiments. This was studied because of the difficulties encountered in proportioning such a small amount of coal uniformly through the concentrates. It was by the addition of propane gas to the air stream that the experimental work progressed, and this feature was provided for in the pilot-plant designs.

Pot-grate tests were also made in which anthracite was coated on the balls, and experiments with this procedure were carried much further at the pilot plant. In all, about 35 pot-grate experiments were carried out to obtain information essential for the design of the pilot plant, and the pot grate is still in use for determining the agglomerating characteristics of various kinds of ore and ore concentrates.

The Grate-Type Machine Pilot Plant

The grate-type machine pilot plant was erected at Carrollville, Wisconsin, adjacent to one of the Allis-Chalmers warehouses, where water, electricity and transportation facilities were available. The plant was mechanized as much as possible to minimize labour requirements and permit the engineers in charge to give maximum attention to the mechanical and metallurgical problems. A number of changes were made to the equipment and in processing during early operations, but it is intended to describe the pilot plant only as it is now and some of the major changes that were made to determine whether the process would be successful on a commercial scale.

The plant can be considered as divided into two sections, the first for the preparation of green balls (or pellets) and the second for heat hardening them. The equipment in each section, however, was so arranged that the plant could be efficiently handled as a single compact producing unit in which all operations could be concurrent and continuous (*see* Fig. 1).

The concentrate storage facilities include a bin of 50 tons capacity inside the building and a stockyard outside but adjacent to the building for an additional 200 tons. Repulping and refiltering of the concentrates are carried out at the pilot plant to obtain a feed of uniform moisture content for making green balls. The concentrate is conveyed from the storage bin to slurry tanks in which a predetermined percentage of solids is maintained. The consistency of the slurry is varied with the nature of the concentrates and the amount of moisture desired in the filter cake. For magnetite concentrates, slurry containing 50–65% of solids was used in the pilot-plant test work, and filter cake containing 9·5–10·0% of moisture was found to be satisfactory for balling.

The slurry is filtered in a 4-ft. dia., 4-ft. wide drum filter (*see* Fig. 3) and the filter cake is conveyed to a small table feeder, which permits the filter to be worked intermittently and independently from the balling-drum circuit, if desired. The filtered concentrate is fed into the balling drum circuit at a predetermined rate—with magnetite, at 2–3 tons/hr. Additives are placed on the balling-drum feed belt by means of a small Syntron vibrating unit. For pelletizing magnetite concentrates, the feed to the drum consisted only of concentrates, bentonite and 'seed' pellets.

The balling drum is 8 ft. long × 3 ft. dia. (*see* Fig. 4). It is equipped with a variable-speed drive so that changing conditions in the balling drum operation can be coped with, and with a cutter bar for maintaining a lining that is conducive to good 'balling.' The product from the drum is screened over a 4 ft. long × 1 ft. wide vibrating screen. The undersize balls from the screen are called 'seed' pellets and these are returned to the charging end of the balling drum (*see* Fig. 5). The formation of pellets has been likened to the growth of snowballs, and the seed pellets are recirculated until they attain the desired size for heat hardening. When making balls $-\frac{1}{2} + \frac{3}{8}$ in. in size, the circulating load under favourable conditions was about 1½ times as much as the

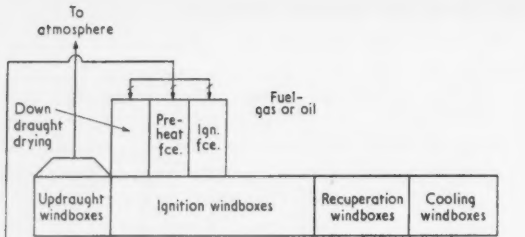


Fig. 9—Air-flow diagram: Carrollville pilot plant

makeup of fresh concentrates, i.e. about 60% of the total feed.

After reaching the desired size, the balls are conveyed to a coal coating drum, 5 ft. long × 3 ft. dia. Anthracite, pulverized to −20 mesh, of the required amount for heat-hardening purposes, is added to the conveyor belt by means of a small table feeder and applied to the surface of the balls by rotation of the drum.

The coal-coated balls are transferred to the grate-type heat-hardening machine by means of a cleated inclined conveyor belt and deposited in a small feed hopper that is equipped with an adjustable back plate, which enables different bed heights to be obtained. Distribution of the pellets on the grate of the machine is effected by means of a swinging conveyor (*see* Fig. 6.).

The design of the grate is essentially the same as that which would be used for a small continuous-type sintering machine. It is 20 ft. 6 in. long between centres of sprockets and 2 ft. wide. The pallets of the grate have side plates 14 in. high × 18 in. long. The windbox under the grate is 17 ft. long and has an effective area of 34 sq. ft., 4 sq. ft. of which, at the feed end, is used for drying by updraught, and the remaining 30 sq. ft. for burning and cooling by downdraught. The downdraught portion of the windbox is designed with adjustable division walls to form three sections. These are designated as (*a*) the ignition section, because of its location relative to the ignition furnace, (*b*) the recuperation section, because of its function in recovering the hot air from the first stage of cooling, and (*c*) the cooling section, where final cooling of the pellets is effected (*see* Fig. 10).

The sectional arrangement of the windbox with various fans, ducts, and valving is an essential feature in recovering and utilizing to the greatest possible extent the heat that would be wasted in an ordinary grate-type machine. The recovered heat is used for drying and preheating the raw pellets and preheating the air for combustion (*see* Fig. 9).

Initially the air from the 'cooling' section of the windbox, being at about 350° F. (177° C.), was utilized for pre-drying the balls in the coal-coating drum, but when this method was supplanted by updraughting on the machine itself the air was then utilized for the latter purpose.

The so-called ignition furnace is a combination of three parts, designated as (*a*) the drying chamber, (*b*) the preheat chamber, and (*c*) the final ignition chamber. The furnace has movable end walls to permit variations in the size of the drying and ignition chambers and to allow raising or lowering of the furnace to accommodate different depths of bed on the grate. Provisions are made for burning propane gas in the ignition chamber.

The gases from the ignition windbox are wasted to atmosphere because of their very high moisture content and low temperature. The air from the recuperation windbox is of high thermal value and is conducted to the ignition furnace. Ordinarily, the only air utilized in the updraught drying chamber and the preheat chamber is that which is recovered from the final cooling section. However, propane gas burners are provided for starting operations and to raise the temperature of the drying medium at other times, if necessary. The air from the recuperation windbox averaged about 700–750° F. (371–500° C.). During the operations on magnetite concentrates the final ignition temperature is maintained at 2350–2400° F. (1287—1316° C.), the temperature required to effect grain growth and cementation of magnetite crystals as they are oxidized to hematite. The arrangement of the ignition furnace, the windbox sections, and the fans is such that part of the air and gases from the recuperation and/or cooling sections can be wasted to atmosphere if they provide more heat than is needed for the process.

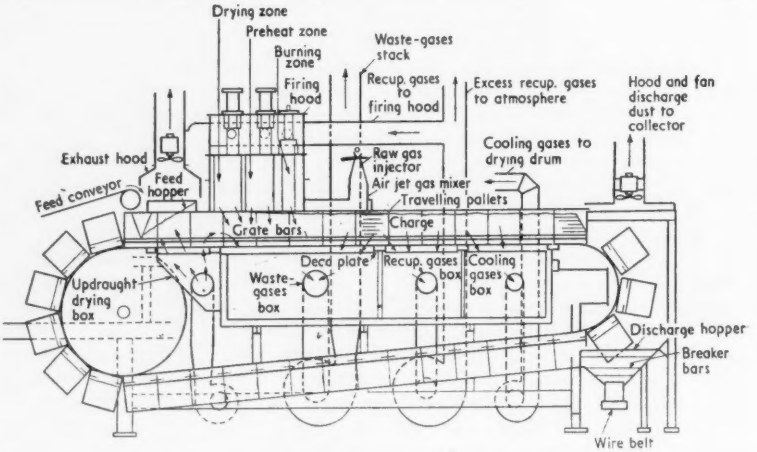


Fig. 10—Grate-type heat-hardening machine: Carrollville pilot plant

The heat-hardened pellets, after discharge from the machine (*see* Fig. 7), are moved by a woven-steel conveyor belt to a double-deck vibrating screen where all −8 mesh material is removed for re-processing. The screened product is then conveyed to a stockpile or collected in drums for testing purposes.

The Carrollville plant is fully equipped with gauges and instruments to permit positive control for each machine and each phase of operations and to provide all the data that are needed in computing quantitative results (*see* Fig. 8). Amongst other records kept during each test are air flows, windbox suctions, and temperatures for each windbox; temperatures and pressures in each chamber of the ignition furnace; recuperated air flows and pressure; differential pressure between the ignition furnace and the ignition windbox; differential pressure across each fan; power readings for each fan; total power readings for the plant; and grate speeds.

Chemical and physical testing of raw materials and of products is carefully performed for correlation with the operating data. The hardened pellets must be strong and tough to resist breakage and abrasion in the severe handling that is unavoidable in a combination of rail and water transportion. In one of the physical tests a 50-lb. sample is revolved 100 times at the rate of 24 rev./min. in a standard A.S.T.M. coke-testing drum. Degradation, as measured by the amount of −10 mesh particles after tumbling, is usually found to be less than 10%.

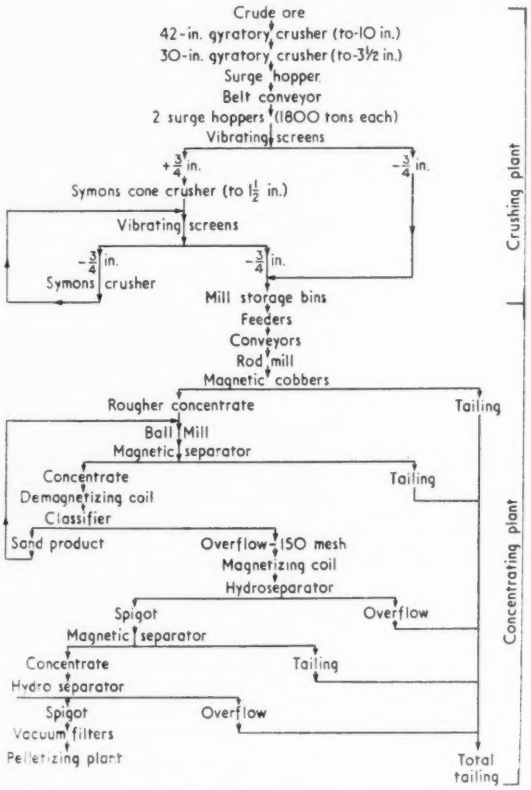


Fig. 11—Flow chart of crushing and concentrating plants: Babbitt (Minn.) plant[5]

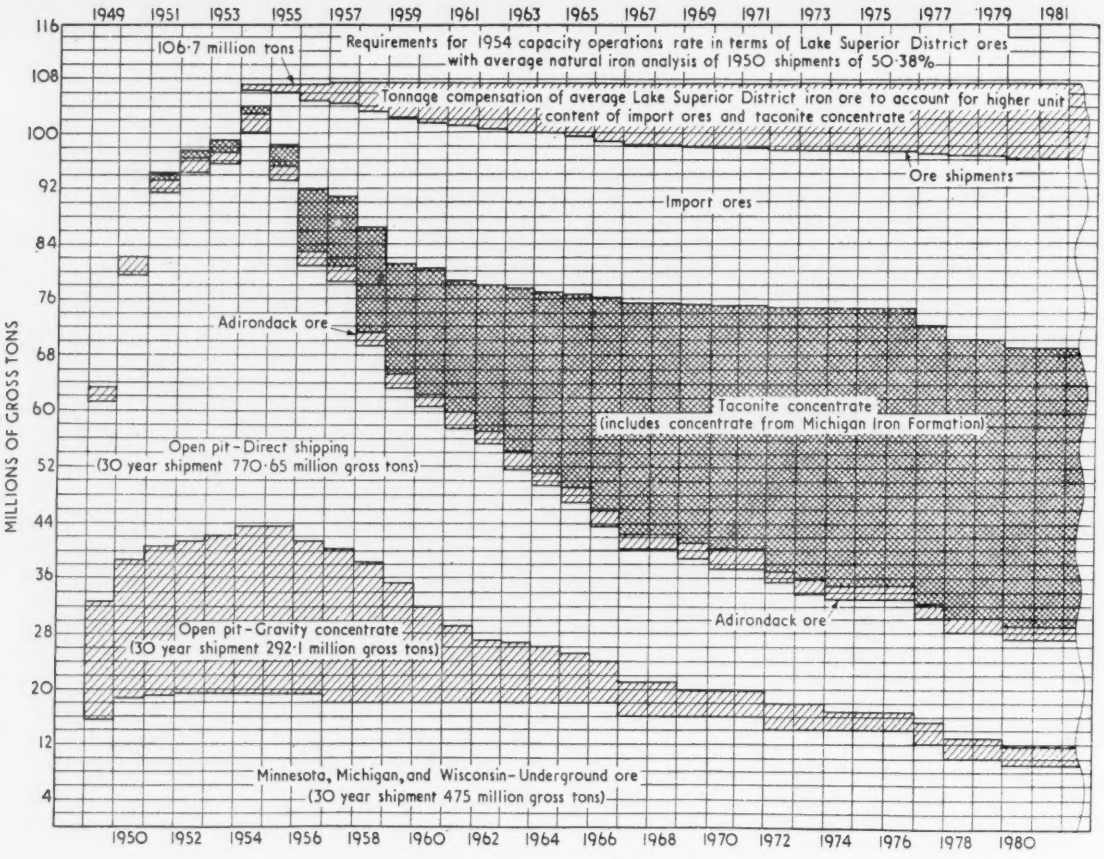
The results obtained from this recuperation grate-type heat-hardening machine and the materials handling and preparing equipment especially designed to support its operations were in most respects superior to those obtained in the small shaft-furnace pilot plant already described. The difficulties encountered were susceptible of analysis and amenable to correction. Most of the metallurgical complications that caused delays in the operation of the shaft furnace did not occur in heat-hardening with the grate-type machine. Output could be maintained with regularity. The quality of the product was more uniform in size and structural stability. Fuel consumption of about 800,000 B.t.u. per ton of product was slightly higher than that of the shaft furnace but much less than that obtainable with a non-recuperative type grate-machine.

First Commercial Grate-Type Machine

At the Carrollville pilot plant the fundamental design information and operating data needed for building a commercial-scale recuperative grate-type unit were obtained. Arrangements were then made with the Reserve Mining Company to install a machine with a theoretical capacity of 1000 tons daily at Babbitt, Minnesota, where facilities for producing taconite concentrates of an equal amount were already in operation (*see* Fig. 11). This grate-type machine, which is 6 ft. wide × 108 ft. long, was placed in service in February, 1954, and its actual capacity is slightly higher than that for which it was designed. The quality of the heat-hardened pellets produced on this machine has been tested by charging them as various proportions of blast-furnace burdens and has been pronounced eminently satisfactory. Their cost, even as produced in this semi-experimental plant, should be considerably less than that of imported iron ores for furnaces that are not located on or near the sea coast. The Babbitt plant operations have demonstrated that the pilot-plant results can be duplicated and probably improved upon in a commercial plant of any desired size.

Using the designs, equipment, and processing methods for agglomeration that were developed in the Carrollville pilot plant and the small commercial unit at Babbitt, an establishment that will initially concentrate and produce from taconites 3,750,000 tons of high-grade ore annually is now being built by the Reserve Mining Company on the shore of Lake Superior at Silver Bay, Minnesota. Ultimately, an annual production of 10 million tons at Silver Bay is planned. Plans are also being completed by the Erie Mining Company for a plant comparable in capacity with that of the Reserve Mining Company. The Erie Mining Company has continued experiments with the shaft-type furnace, and will have a choice between the two methods of heat hardening described in this paper.

From the plants mentioned, about 630,000 gross tons of agglomerated taconite concentrates were shipped to blast-furnaces during 1954. Of this total, about 150,000 tons were sintered, 300,000 tons


1949 1951 1953 1955 1957 1959 1961 1963 1965 1967 1969 1971 1973 1975 1977 1979 1981
116
108
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12
4
MILLIONS OF GROSS TONS
106·7 million tons
Requirements for 1954 capacity operations rate in terms of Lake Superior District ores with average natural iron analysis of 1950 shipments of 50·38%
Tonnage compensation of average Lake Superior District iron ore to account for higher unit content of import ores and taconite concentrate
Ore shipments
Import ores
Adirondack ore
Taconite concentrate (includes concentrate from Michigan Iron Formation)
Open pit–Direct shipping (30 year shipment 770·65 million gross tons)
Adirondack ore
Open pit–Gravity concentrate (30 year shipment 292·1 million gross tons)
Minnesota, Michigan, and Wisconsin–Underground ore (30 year shipment 475 million gross tons)
1950 1952 1954 1956 1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980

Fig. 12—Sources of iron ore for Great Lakes region steelplants, projected for 30 years (reproduced by courtesy of V. D. Johnston)

nodulized, and 500,000 tons were in the form of pellets. It is estimated that by 1961 the taconites will account for about 10,000,000 tons of blast-furnace and open-earth ores which, in metallic content, will be the equivalent of about 12,000,000 tons of the average grade of ore at present being shipped from the Lake Superior District (*see* Fig. 12).

Further utilization of the taconites can be increased as needed to compensate for the diminishing supply of direct shipping and other Lake Superior ores. With reserves thus vastly augmented, the Lake Superior region should continue indefinitely as a domestic source for most of the iron ore used in U.S. blast-furnaces. This development serves to emphasize, again, the increasingly important role of iron-ore beneficiation in the manufacture of pig iron.

Acknowledgments

The author gratefully acknowledges material and other assistance received from officials and staff of Arthur G. McKee and Company, the Allis-Chalmers Manufacturing Company, and the Reserve Mining Company. Many of these have been actively engaged in the design and operation of the equipment and plants that have been described or mentioned in the paper.

References

1. J. W. GRUNER: "Mineralogy and Geology of the Taconites and Iron Ores of the Mesabi Range," p. 27: 1946, St. Paul, Minn., Iron Ore Resources and Rehabilitation and Minnesota Geological Survey.
2. G. D. ELLIOT: "Ironmaking at Appleby-Frodingham," Spec. Rep. No. 30, pp. 8–29: 1944, London, The Iron and Steel Institute.
3. E. W. DAVIS: Mines Experimental Station, University of Minnesota, Information Circular No. 6, Jan., 1951.
4. R. L. BENNETT, R. E. HAGEN, and M. V. MIELKE: *Min. Eng.*, 1954, vol. 6, pp. 32–38.
5. *Iron Age*, 1953, vol. 170, 12th Mar., pp. 125–134.
6. J. W. GRUNER: *Min. Eng.*, 1954, vol. 6, pp. 287–288.

The Strain Ageing of Alpha-Iron

By W. R. Thomas, B.A.Sc., M.A.Sc., Ph.D., and G. M. Leak, B.Sc., Ph.D.

SYNOPSIS

Measurements have been made of the rates of strain ageing of specimens of α-iron containing carbon, and α-iron containing nitrogen at various temperatures. Activation energies for strain ageing have been estimated as 20·4 kcal./mole for carbon and 18 kcal./mole for nitrogen, values in close agreement with the respective activation energies for diffusion of these solutes in α-iron. The rates of strain ageing agree with the $t^{\frac{2}{3}}$ law of Cottrell and Bilby up to 50–60% completion of the process. It is shown that the number of dislocations introduced into a freshly quenched specimen by a given strain is dependent on the number of solute atoms.

Calculations of the density of the dislocation atmospheres give 10–15 atoms per atom plane of dislocation. This confirms the suggestion of other investigators that precipitation is likely to occur.

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STRAIN AGEING and yield-point phenomena in α-iron have already been shown[1–4] to be caused by the migration of the interstitial solute atoms, carbon and nitrogen, into dislocations, to form anchoring atmospheres. Then $n(t)$, the number of solute atoms per unit volume of material that have migrated into dislocations at temperature T after time t is given by

$$n(t) = \alpha n_0 L\left(\frac{ADt}{kT}\right)^{\frac{2}{3}} \quad \ldots\ldots(1)$$

Here n_0 is the solute concentration in the material at zero time, D the diffusion coefficient of the solute, L the total length of edge dislocations per unit volume, α a numerical constant, and A a constant depending on the strain introduced into the lattice by a solute atom. This expression applies only to the initial stages of ageing. Harper[5] suggested that in the later stages account could be taken of the competition between partially filled atmospheres by letting the rate of removal of solute atoms be proportional to the concentration left in solution at any instant. Thus considering q as the fraction of solute which has migrated to dislocations ($q = n(t)/n_0$) then

$$\frac{dq}{dt} = (1 - q)\alpha L\left(\frac{ADt}{kT}\right)^{\frac{2}{3}} \quad \ldots\ldots(2)$$

Hence for the later stages of ageing

$$\ln(1 - q) = \alpha L\left(\frac{ADt}{kT}\right)^{\frac{2}{3}} \quad \ldots\ldots(3)$$

Harper's measurements showed that this gave agreement with experimental observations, almost to completion of ageing.

Migration of solute atoms to more ordered sites in dislocation atmospheres affects electrical resistivity.[6] Dahl and Lücke[7] followed the ageing process by this method and estimated that between 20 and 50 solute atoms migrated to each dislocation per atom plane. Such a concentration could not merely be bound to the dislocation but must form a precipitate. There is evidence, however, that the binding energy of the solute in a dislocation is greater than for a precipitate.[8] Cottrell and Leak[9] investigated the effect of quench ageing on strain ageing; their results suggested that fine precipitate particles formed at low quench-ageing temperatures redissolved to provide solute atoms for dislocations upon subsequent strain ageing. A calculation based on Dijkstra's measurements[10] of the solubility of nitrogen in cold-worked α-iron show that the binding energy of a nitrogen atom in a dislocation is about 0·45 eV. compared with about 0·35 for the nitride.

There is some evidence[11] that boron forms an interstitial solution in α-iron. Consequently, boron might also give rise to quench- and strain-ageing phenomena.

The purpose of the present investigation was to obtain precise data on the rates of strain ageing on specimens that contained only nitrogen and on specimens that contained only carbon. The results of many previous investigations have not been amenable to rigorous analysis because the specimens have contained both solutes. Wert[12] has shown that the presence of both in the specimen can exert a marked influence on the measured rate of strain ageing and it is therefore imperative that the effects of carbon, for instance, are not distorted by the presence of nitrogen.

EXPERIMENTAL DETAILS

Most of the measurements were made by internal friction methods. The technique has been adequately described elsewhere[13] so that only a brief description will be given here. Specimens in the form of wire constitute the suspension of a torsional pendulum. The pendulum is set into vibration by means of electromagnets and the logarithmic decrement is measured. A plot of the logarithmic decrement against temperature for a fixed frequency of oscillation shows a maximum in the curve, characteristic of the solute present. The height of the maximum is proportional to the amount of solute in free solution and the temperature at which the maximum occurs depends on the diffusion coefficient of the solute and the frequency of oscillation. Frequencies of oscillation ranged from 1 to 15 cycles/sec. It was found convenient to determine the temperature at which the maximum of the relaxation peak occurred for a given frequency and to age at this temperature. By this

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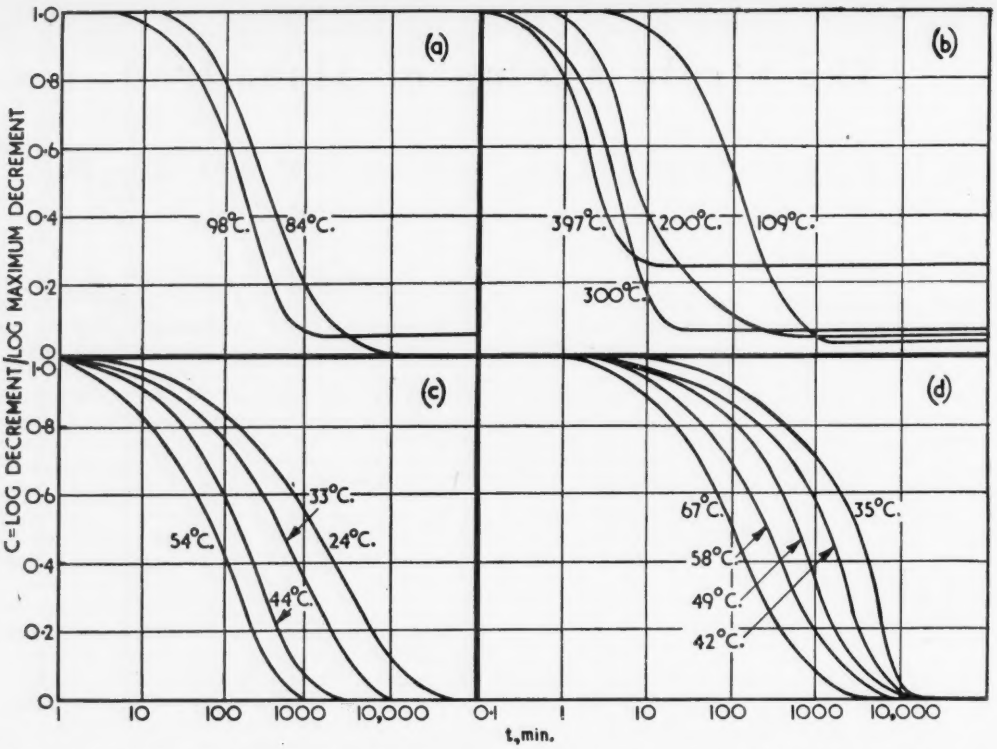

Fig. 1—Quench ageing of (*a*) nitrogen-iron (0·015 wt.-% N) and (*b*) carbon-iron (0·015 wt.-% C); strain ageing of (*c*) nitrogen-iron (0·015 wt.-% N) and (*d*) carbon-iron (0·015 wt.-% C)

means it was possible to follow the process without removing the specimen from the internal friction apparatus and to record the measurements photographically and automatically.

It was considered necessary to compare the results obtained by the internal friction method with the results obtained by the more conventional method of measuring the rate of return of the yield point. Some of the measurements were, therefore, determined by both methods for the same temperature of ageing and the same concentration of solute. A simple vertical tensile machine was used for yield-point measurements. The applied load was measured with an optical lever from the elastic deflection of a steel beam

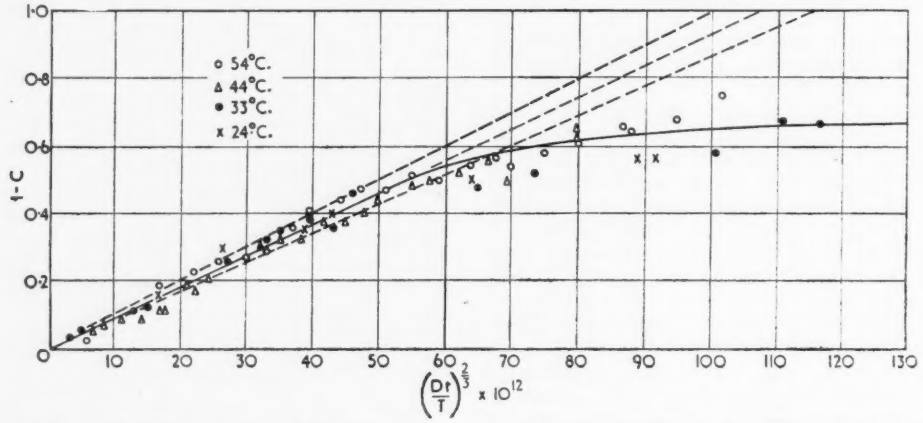

Fig. 2—Strain ageing of nitrogen-iron (0·015 wt.-% N) at various temperatures *v.* $(Dt/T)^{\frac{2}{3}}$, where *t* is in minutes

connected to the top of the specimen. To measure the extension of the specimen precisely, a form of Martens' extensometer was used. Over a gauge length of 5 in. the strain sensitivity of this arrangement was better than 10^{-6} and more than adequate for the purposes of this investigation.

Specimens were prepared from pure iron (B.I.S.R.A. reference *AHN*) of the following analysis:

	Batch Analysis, %	Check Analysis, %
C	0·002–0·004	0·0038
Si	0·002–0·003	0·001
Mn	0·004	0·005
S	0·004–0·006	
P	0·001	
Ni	0·010	
Cr	0·001	0·0013
Cu	0·004–0·007	
Al	0·001	0·0027
O_2	0·001–0·002	
N_2	0·001–0·002	0·0014
H_2	0·000005	

This material, in the form of $\frac{1}{8}$-in. wire, was annealed at 700° C. in flowing wet hydrogen for 5 days, which reduced the carbon and nitrogen contents to amounts that were below the limits of detection by chemical analysis or internal friction measurements, i.e. $< 0{\cdot}0005$ wt.-%. Specimens were drawn down to diameters of 0·080, 0·040, and 0·030 in. and were approximately 10 in. long.

Production of Nitrogen Specimens

Nitrogen was introduced into the specimens by heat-treatment at 700° C. in a silica tube from which the air had been evacuated and replaced with a mixture of hydrogen and ammonia gas. The pressure of the mixture was about $\frac{1}{3}$ atm. at room temperature to give a pressure near atmospheric in the tube at 700° C. Adjustment of the quantity of ammonia gas and hence the total available nitrogen made it possible to produce homogeneous specimens with a fairly wide range of nitrogen contents, 0·001–0·030 wt.-%. After nitriding in the mixture for 12 hr. it was found unnecessary to give the specimens a further homogenizing treatment.

Production of Carbon Specimens

Several methods of introducing carbon into the specimens were tried and rejected either because they produced inhomogeneous specimens or were difficult to control. The method recommended by several investigators in which hydrogen saturated with a volatile hydrocarbon, such as heptane, is passed over the specimens held at a temperature of 700° C. was found to produce erratic results.

The most satisfactory results were obtained by sealing specimens in a silica tube with carbon of spectrographic purity and an atmosphere of CO and CO_2, and allowing the system to equilibrate at 700–800° C. This produced specimens with carbon contents ranging from 0·001 to 0·02 wt.-%. The carbon content was controlled by varying the quantity of powdered carbon available for the reaction.

Quenching of Specimens

Before measurement the specimen was sealed in hard glass at a pressure of 1μ Hg or less, 'soaked' at temperature for 15 min. and quenched into cold water to retain all solute in free solid solution. The nitrogen specimens were checked several times for loss of nitrogen and none was detected. Nitrogen specimens were quenched from 580° C. and carbon specimens from 700° C.

For quench-ageing measurements the wires were tested immediately after quenching. Ageing was carried out in oil baths with a temperature fluctuation of $\pm 1{\cdot}0$° C.

For strain-ageing measurements the wires were strained 7% in a small Denison tensile machine immediately after quenching. The ageing temperatures were generally lower than those for quench ageing and it was possible to age the wires in the furnace of the internal friction apparatus as discussed above.

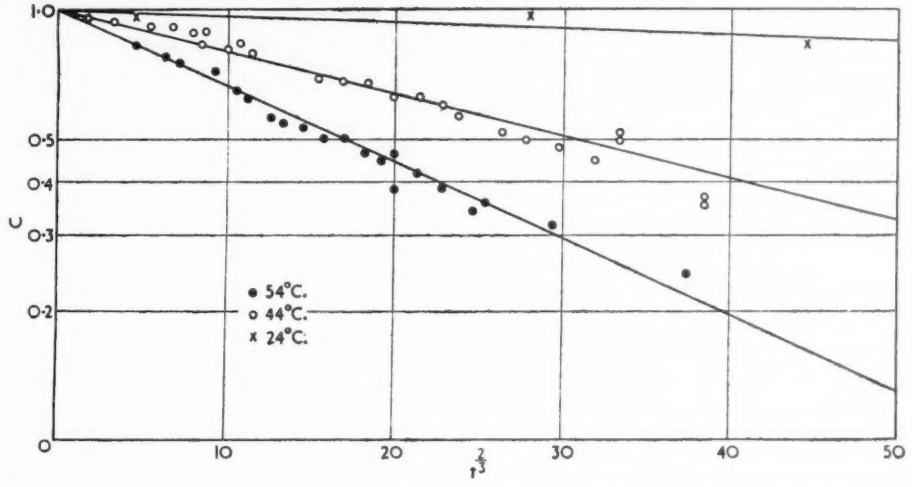

Fig. 3—Strain ageing of nitrogen-iron (0·015 wt.-% N) at various temperatures plotted as *C* (log scale) *v.* $t^{\frac{2}{3}}$, where *t* is in minutes

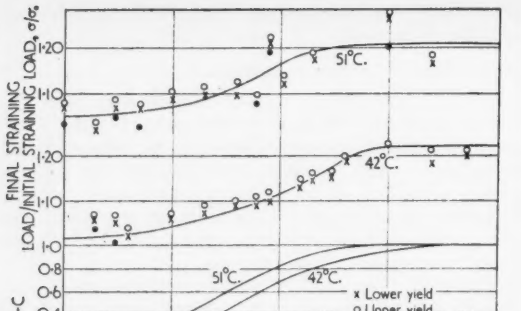

Fig. 4—Strain-ageing curves of nitrogen-iron (0·029 wt.-% N) obtained by two methods of testing

EXPERIMENTAL RESULTS

Iron–Nitrogen Specimens

Typical (internal friction)–(log time) curves for strain ageing are shown in Fig. 1*c* for four temperatures of ageing.

The ordinate C represents the internal friction value divided by the maximum value at the start of ageing and thus represents the fraction of original solute still in free solution at any time. Background damping has been subtracted in all curves. This plot enables curves for different temperatures and different concentrations to be compared.

For comparison, two of the quench-ageing curves for similar specimens are shown in Fig. 1*a*. It can be seen that the temperature has to be increased considerably before the rate of quench ageing approaches that of strain ageing. The results for quench ageing can be extrapolated down to a temperature of 54° C. for a more direct comparison. This gives a time to half completion about 20 times longer than the comparable time for strain ageing at 54° C. It is apparent that the strain-ageing results are not distorted by quench ageing, since strain ageing is completed before quench ageing begins.

Since the mechanism of strain ageing is the removal of solute atoms from free solution, $q = 1 - C$ represents the fraction of the original solute which has been absorbed by dislocation atmospheres. In accordance with the Cottrell–Bilby theory,

$$q = 3L\left(\frac{\pi}{2}\right)^{\frac{1}{2}}\left(\frac{A\,Dt}{kT}\right)^{\frac{2}{3}} \qquad \ldots\ldots(4)$$

an expression similar to equation (1).

A plot of q against $(Dt/T)^{\frac{2}{3}}$, Fig. 2, gives a straight line up to the value of $q \simeq 0{\cdot}5$, when the rate of strain ageing diminishes rapidly. As mentioned, the Cottrell–Bilby theory does not take into account the interaction and competition of partially filled atmospheres. The equation (3) of Harper gives a straight line almost to the completion of strain ageing. This is shown in Fig. 3 where C (on a log scale) *v.* $t^{\frac{2}{3}}$ is plotted for various temperatures of ageing.

The dislocation density L can be calculated from the results by determining the slope of a curve of q plotted against $(Dt/T)^{\frac{2}{3}}$. This was done for specimens containing 0·015% N: taking $A \simeq 1{\cdot}5 \times 10^{-20}$ dyne cm.^{2} gave $L = 7{\cdot}7 \pm 0{\cdot}2 \times 10^{10}$ lines/sq. cm. for a strain of 7%. A corresponding value interpolated from Harper's results is 2×10^{11} lines/sq. cm.

Comparison of Methods of Test

Identical specimens were tested at the same temperatures of ageing both by the internal friction method and by the measurement of yield point. These data are plotted in Fig. 4. The ordinate of the yield-point curve is the ratio of the measured yield stress to the initial straining load and the ordinate of the internal friction curve is q as defined above; the abscissae of both are the logarithms of time. The curves show very good agreement between the two methods. The experimental points for the internal friction method are not shown because they lie very close together and fit the lines. The scatter of experimental points in the yield-point method is considerably greater. On the basis of this agreement the authors considered it fair to compare the data for strain-ageing rates obtained by both methods. The yield-point measurements show the rate of arrival of solute atoms at the dislocations whilst the internal

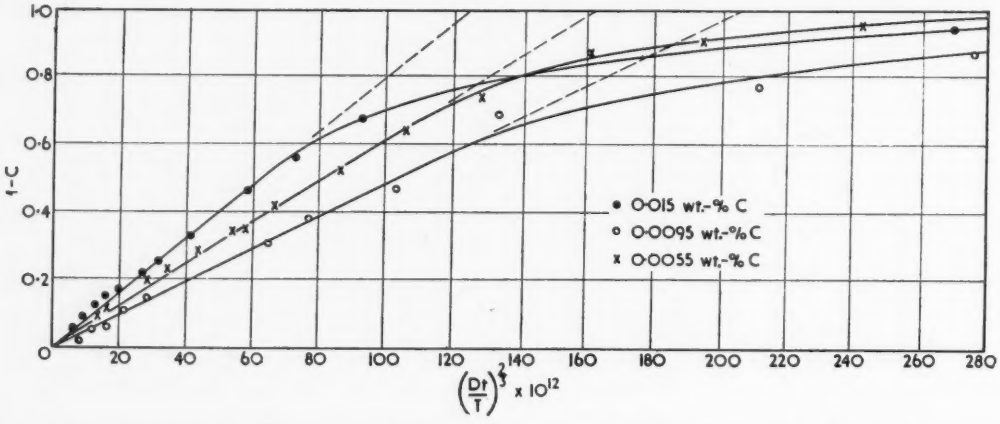

Fig. 5—Strain ageing of carbon-iron containing various amounts of carbon *v.* $(Dt/T)^{\frac{2}{3}}$, where t is in minutes

friction measurements give the rate of removal of solute atoms from free solution. The results given in Fig. 4 show that these techniques are complementary.

Iron–Carbon Specimens

The strain-ageing curves for iron–carbon specimens at five different temperatures are given in Fig. 1*d*. For comparison, quench-ageing curves for iron–carbon are also shown in Fig. 1*b* and it can be seen that the temperature of ageing has again to be increased considerably before the rate approaches that of strain ageing.

If these data are plotted against $(Dt/T)^{\frac{1}{3}}$, as in Fig. 5, the straight-line relationship holds up to at least $q \simeq 0{\cdot}6$ and the lines for specimens containing different amounts of carbon do not coincide.

A different density of dislocations can be calculated for each concentration of carbon: a plot of this is shown in Fig. 6 as dislocation density v. the weight-percentage of carbon.

Activation Energy for Strain Ageing

An activation energy for the process of strain ageing can be derived from the ageing curves in Figs. 1*c* and *d*, if it be assumed that the time taken to reach a certain stage at any temperature T is given by a factor of the form $\exp(Q/RT)$. The logarithms of the times corresponding to $C = 0{\cdot}25$ and $0{\cdot}5$ are plotted against $1/T$ in Fig. 7.

The best value of Q for nitrogen from Fig. 7 is 18 kcal./mole. This value is in excellent agreement with the activation energy for the diffusion of nitrogen in α-iron.[14] Similarly a value of Q for strain ageing caused by carbon is found to be $20{\cdot}4$ kcal./mole; this is again in good agreement with the data for the diffusion of carbon in α-iron.[15]

This result was to be expected since the work of previous investigators had indicated that the strain-ageing process is dependent on the diffusion of interstitial solute.

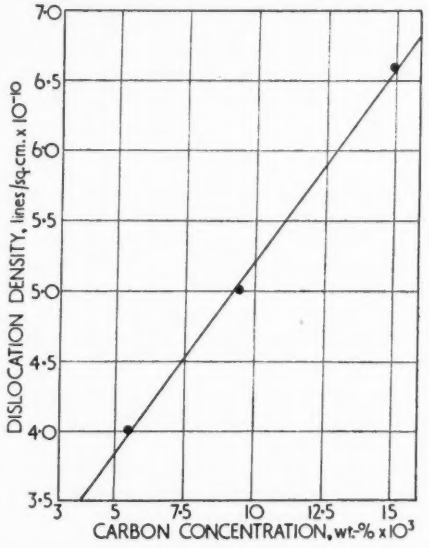

Fig. 6—Variation of dislocation density with concentration of carbon in iron after 7% strain

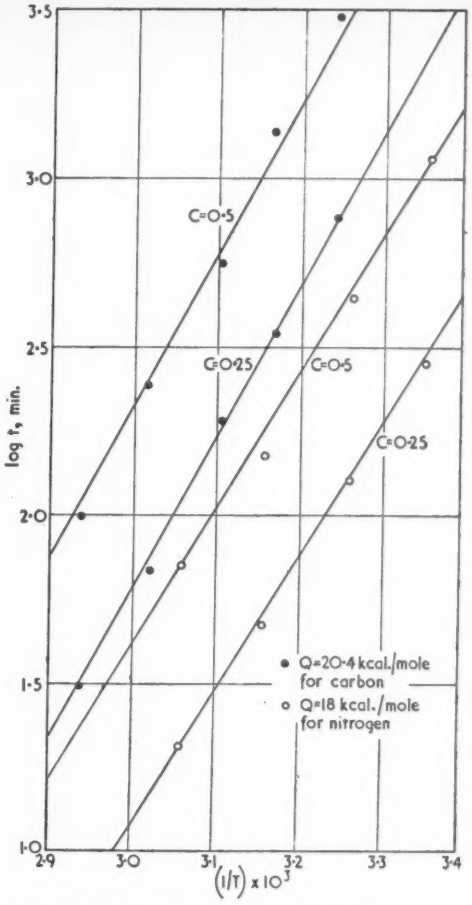

Fig. 7—Activation energy for strain ageing after 7% strain

DISCUSSION OF RESULTS

It is apparent from Figs. 2 and 5 that the $t^{\frac{1}{3}}$ law derived by Cottrell and Bilby adequately describes the initial stages of the strain-ageing process. Harper's suggestion for using a logarithmic function with the $t^{\frac{1}{3}}$ law takes into account the interaction and competition of partially filled atmospheres giving a straight line (Fig. 3) almost to the completion of the strain-ageing process.

From the equation for the rate of strain ageing (4) the dislocation density introduced by a given strain can be calculated. The value of A, a parameter depending on the elastic constants, the volume change caused by the solute, and the strength of the dislocation, is given by

$$A = Ur/\sin\theta$$

where r and θ are the polar co-ordinates of the solute atom, measured from the dislocation, and U is the binding energy of the solute atom in the dislocation. Recent measurements by the authors of the binding

Table I

ESTIMATED DENSITY OF DISLOCATION ATMOSPHERES AFTER STRAIN AGEING

Investigator	Strain, %	Nitrogen, wt.-%	Carbon, wt.-%	Dislocation Density $L \times 10^{-10}$, lines/sq. cm.	Number of Solute Atoms per Atom Plane
Present work	7	0·015	...	7·7	11·5
	7	...	0·015	6·6	15·6
	7	...	0·0095	5·0	13·1
	7	...	0·0055	4·0	9·4
Dahl and Lücke[7]	4·5		0·015	0·82	75
	5·1		0·015	1·67	45
	5·3		0·018	0·95	118
Harper[5]	5		0·015	18·6 (7·7*)	13
	10		0·009	24·6 (10·2*)	6
	15		0·013	37·2 (15·7*)	6

* Corrected

energy of a nitrogen atom in a dislocation indicate that $U = 0{\cdot}42$ eV. Taking $r = 2 \times 10^{-8}$ cm. at $\theta = 3\pi/2$ gives $A \simeq 1{\cdot}4 \times 10^{-20}$ dyne cm.^{2}, a value in good agreement with that estimated by Cottrell. The values of the dislocation densities calculated from the present results and the results of other investigators are summarized in Table I. Harper does not state the value of A used in his calculation but a re-assessment of his results indicates that he has taken $A \simeq 3 \times 10^{-20}$ dyne cm.^{2}, and $\alpha = 2(\pi/2)^{\frac{1}{2}}$ instead of $\alpha = 3(\pi/2)^{\frac{1}{2}}$, making his estimations of dislocation densities too high by a factor of 2·4. This does not change their relative values.

The variation of dislocation density with concentration of solute, Fig. 5, is to be expected. It means that the number of dislocations required to produce a given strain in the freshly quenched iron, in this case 7%, increases with the number of solute atoms present. Analogous cases can be found in both ferrous and non-ferrous alloy systems where the rate of work-hardening increases with increasing solute concentration. Current theory[16] suggests that solution hardening can be caused only by groups of solute atoms. This may indicate that the carbon atoms in a specimen of iron quenched from 700° C. tend to cluster rather than being distributed in random solution.

The density of the dislocation atmosphere can be calculated from the expression

$$Z = \frac{x\rho Na}{ML}$$

where x = Solute in dislocations, wt.-%
ρ = Density of the specimen, g./c.c. ($\simeq 8$)
N = Avogadro's number
a = Lattice parameter of iron ($2{\cdot}86 \times 10^{-8}$ cm.)
M = Atomic weight of the solute.

Assuming that the dislocations are saturated when 60% of the available solute atoms are removed from free solution (Figs. 2 and 5), the calculated densities are shown in Table I, together with those given by Dahl and Lücke. The same assumption has been made for Harper's results and the calculated densities are also shown in Table I, although no weight is attached to these since it is unfair to make such assumptions without the complete experimental data. These values are very much higher than that originally proposed by Cottrell and Bilby, who estimated that there was room for two atoms per atom plane, one in the core of the dislocation and one in the dilated field around the core. Dahl and Lücke suggest that precipitation must be occurring, since it is not possible for the dislocations to absorb so many solute atoms in their stress fields. If two atoms per atom plane is accepted as the saturation value the excess must form precipitate. It is interesting to note that the $t^{\frac{1}{3}}$ law is valid far beyond the saturation of the dislocations. This would indicate that the dislocations are continuing to act as sinks for the solute atoms and, therefore, precipitation must be removing atoms from the dislocation. It has been shown that the binding energy of a solute atom is greater in a dislocation than in the precipitate. This value, however, is applicable only to the solute atom near the core where the interaction is a maximum. There should exist a spectrum of interaction energies for the solute atoms ranging from this maximum to zero, in which there will be a range that can be attracted by the precipitate.

CONCLUSIONS

(1) Strain ageing is a process with an activation energy identical with that for the diffusion of the interstitial solute responsible for the phenomenon ($Q = 18$ kcal./mole for nitrogen, $Q = 20{\cdot}4$ k cal./mole for carbon).

(2) The rate of strain ageing follows closely the $t^{\frac{1}{3}}$ law of Cottrell and Bilby up to 50–60% completion of the process.

(3) The number of dislocations introduced by a given amount of strain is dependent on the number of interstitial solute atoms present.

(4) The density of the dislocation atmosphere is too large to be considered merely an atmosphere and precipitation must occur.

(5) Internal friction and yield-point measurements give identical information about the strain-ageing mechanism.

Acknowledgments

The authors are grateful to Professor A. H. Cottrell for his continued interest and encouragement in this project. They also wish to acknowledge the able assistance of Mr. B. Fitton who carried out much of the experimental work.

References

1. J. L. Snoek: *Physica*, 1941, vol. 8, pp. 734–744.
2. A. H. Cottrell: "Report on Strength of Solids," pp. 30–38: 1948, London, Physical Society.
3. F. R. N. Nabarro: *Ibid.*, pp. 38–45.
4. A. H. Cottrell and B. A. Bilby: *Proc. Phys. Soc.*, 1949, ser. A, vol. 62, pp. 49–62.
5. S. Harper: *Phys. Rev.*, 1951, vol. 83, pp. 709–712.
6. A. H. Cottrell and A. T. Churchman: *J. Iron Steel Inst.*, 1949, vol. 162, pp. 271–276.
7. W. Dahl and K. Lücke: *Arch. Eisenhüttenwesen*, 1954, vol. 25, pp. 241–249.
8. J. H. Andrew and E. M. Trent: *J. Iron Steel Inst.* 1938, vol. 138, No. II, pp. 241P–288P.
9. A. H. Cottrell and G. M. Leak: *Ibid.*, 1952, vol. 172, pp. 301–306.
10. L. J. Dijkstra: *Trans. Amer. Inst. Min. Met. Eng.*, 1949, vol. 185, pp. 252–260; *J. Met.*, 1949, vol. 1, Mar.
11. W. R. Thomas and G. M. Leak: To be published.
12. C. A. Wert: *Acta Met.*, 1954, vol. 2, pp. 361–367.
13. T. S. Kê: *Trans. Amer. Inst. Min. Met. Eng.*, 1948, vol. 176, pp. 448–476.
14. W. R. Thomas and G. M. Leak: *Phil. Mag.*, 1954, vol. 45, pp. 656–659.
15. W. R. Thomas and G. M. Leak: *Ibid.*, pp. 986–987.
16. E. R. Parker and T. H. Hazlett: *Amer. Soc. Metals Seminar on Relation of Properties to Microstructure*, 1953, pp. 30–70.

Reproducibility of Wöhler-type Fatigue Tests

By J. Clayton-Cave, R. J. Taylor, B.Sc., F.S.S., and E. Ineson, B.Sc., F.I.M.

SYNOPSIS

The variabilities of fatigue test results obtained from (1) individual testing machines, (2) a battery of 12 testing machines of identical design, and (3) a number of testing machines of similar design in different laboratories have been studied in an experiment permitting statistical planning and analysis of results. It is concluded that fatigue data provided by a batch of machines in one laboratory are more variable than those provided by an individual machine. An increase in variability of 37% was found when testing a 0·24% carbon steel (B.S. En.24) at ± 17·5 tons/sq. in. with 12 testing machines. Data provided by more than one laboratory are even more variable.

The influence of small changes in design of test pieces on the variability of test results has been studied and found to be non-significant whilst a common critical section is maintained. 1143

THE FATIGUE TESTING LABORATORY of B.I.S.R.A. was established in 1952 to carry out a programme of research into the effect of various metallurgical factors on the fatigue properties of alloy steels. Twelve testing machines of the rotating-beam type were installed for this purpose. The use of several testing machines, although of identical design, introduces an additional source of variation which may mask small effects of metallurgical factors if the variability between machines is sufficiently high. The scattered nature of fatigue data is well known and an increase in this scatter must be offset by collection of more data. In fact, as the number of testing machines is increased the total number of tests required to investigate a given factor must also increase, although the number of tests per machine will decrease. A statistical approach to the planning of experiments reduces the experimental labour needed for a stipulated degree of precision, but if small effects are to be studied a large sample is still required. It is possible to plan each experiment so that machine effects are evenly balanced among every factor being investigated, but nevertheless the size of these effects must be known to ensure the optimum use of the machines.

A search of the literature for information on testing-machine variability proved fruitless, and, whilst there is a mass of fatigue data available, it is not presented in sufficient detail to enable such information to be deduced. Various authors[1–3] have drawn attention to factors which affect the scatter of fatigue test results, but none appear to have considered machine-to-machine differences. Weibull[4] has stated that in the case of a particular type of direct-stress testing machine the probability is that 40% of the scatter of fatigue test results at a given stress level can be attributed to the testing machine. However, he refers to scatter of results from a single machine and reaches his estimate from empirical calculation and not directly from practical investigation.

Because of the lack of information it was decided first to investigate the performance of the 12 machines at the B.I.S.R.A. laboratory in an experiment which would permit, in addition, the establishment of testing techniques and standards of test-piece preparation which have to be acquired by a new laboratory. An experiment was devised in which the variation in

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Mr. Clayton-Cave is in the Metallurgy (General) Division, of which Mr. Ineson is Laboratory Head, and Mr. Taylor is in the Operational Research Section of the Association.

Table I
CO-OPERATING LABORATORIES

Laboratory Code Letter	Number of Machines	Design of Test Piece Used (see Fig. 1)
T	12	A(H) and F
U	4	A
V	2	B
W	2	C
X	2	G
Y	3	D
Z	6	E

endurance at a given stress level could be divided into two components, one due to specimens and the other due to the testing machines.

Considerable interest in the experiment was shown by other laboratories associated with B.I.S.R.A., and in consequence its scope was extended to include testing machines of a similar design in those laboratories. This involved a complication, as all did not use a common design of test piece, and further work had to be done to ensure that the results were not invalidated by this new factor.

TESTING FACILITIES

In choosing suitable machines for investigating the effect of metallurgical variables on the fatigue strength of steel it was appreciated that the conventional single-point-load Wöhler test (i.e. a rotating-bar cantilever test) has strict limitations. The chief of these concerns the small volume of material actually subjected to maximum stress. This small volume might not necessarily contain the particular metallurgical condition under consideration (e.g. a certain array of non-metallic inclusions) and hence the test would be invalid. By subjecting an appreciable length of test bar to a uniform stress, however, there would be a much greater chance for such a metallurgical condition to play a part in the fatigue failure. This can be achieved either by using conical test pieces in which the taper is designed to compensate for the stress gradient, or by using a two- or four-point Wöhler-type test in which the test piece becomes a uniformly, or nearly uniformly, loaded rotating beam.

The testing machines in this investigation were all of the uniformly loaded rotating-beam type, the majority using the two-point method. Assessment of the surface stress imposed by this system has been referred to elsewhere.[5] Information about the co-operating laboratories is given in Table I, which refers to each laboratory by a code letter and gives the number of testing machines made available by them. The particular designs of test piece which each laboratory normally handles are listed. Details of the differing test piece designs are shown in Fig. 1.

With the exception of the two machines used by laboratory *X*, all the testing machines were basically similar and of the type designed by the N.P.L., briefly described by Phillips.[6] The machines in the B.I.S.R.A. laboratory (*T*) are driven individually by $\frac{1}{2}$-h.p. D.C. motors connected through potential dividers to give comprehensive speed control over the range 0–5000 r.p.m. In the other variations of the basic type, differences were principally connected with the operating speed and the method adopted for loading the test piece. The operating speeds ranged from 2000 r.p.m. in one laboratory to 5000 r.p.m. in another; it is, however, considered that within this range speed has little or no effect on the test results provided that natural resonance peaks are avoided (*see* Appendix).

Laboratory *W* normally used a composite test piece, but this was modified by arrangement to permit a test piece to be handled which conformed more closely with those used by other laboratories.

The two machines in laboratory *X* were of the four-point loading type, generally known as the R. R. Moore type, and adequately described in the literature.[7] The comparison of this type of testing machine with the two-point loading type is of particular

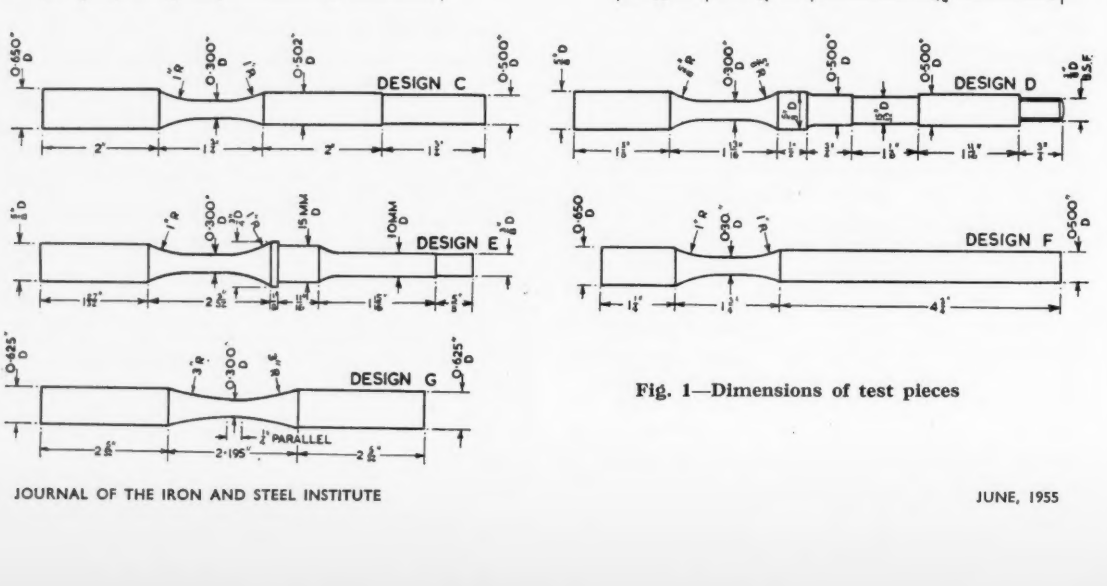


Fig. 1—Dimensions of test pieces

interest, since both are designed to produce a constant moment over the critical section of the test piece.

MATERIAL

The whole investigation has been carried out with material to B.S. 970 specification En.4, i.e. a low-carbon steel of the following nominal composition:

C	Si	Mn	P	S
0·24%	0·24%	0·54%	0·028%	0·047%

It was thought that metallurgical variations of this material would not be so large as to mask the influence of the factors being investigated. An ingot weighing approximately 30 cwt. from a cast of acid open-hearth steel was obtained for the experiments. This was subsequently reduced by hot-rolling to produce 50 lengths of $\frac{7}{8}$-in. dia. round bar. Considerable care was taken with identification during the stages of rolling, so that a complete history of any particular test piece in relation to its position in the original ingot would be known. The bars were numbered 1–50, starting with bar 1 at the bottom of the ingot.

The heat-treatment of the bars consisted of normalizing, tempering, and slow cooling (*see* Table II). The object of the tempering and slow-cooling treatment was to suppress any tendency for the material to age. Two normalizing temperatures were used, but both were within the usual range for this steel and no material variations are believed to have been introduced by this slight difference in temperatures. In each condition the structure was a normal ferritic pearlite, with a slight tendency for the carbides to be spheroidized. The grain size of all samples was A.S.T.M. 8.

Mechanical properties of the heat-treated material as determined from many tensile tests are shown in Table III.

There is an overall variation in U.T.S. of about 3 tons/sq. in. from bottom to top of the ingot. For this reason the test pieces used in each experiment were randomly selected from only one of the three groups shown in Table III.

PREPARATION OF FATIGUE TEST PIECES

All test pieces used in the investigation have been prepared under identical conditions in one laboratory and by one operator, to ensure, as far as was practicable, a uniform standard of finish. There was some evidence that a uniform standard was achieved only after the first 144 test pieces, but as those were used in one self-contained experiment, the influence of surface condition should not affect the final analysis.

Table II
HEAT-TREATMENTS

Bar Numbers	Normalizing Temp., °C.	Tempering Temp., °C.	Batching	Other Treatments
1–8	890	600	Short lengths	None
9–29	920	600	Long bars	Cold-reeled after normalizing
30–50	920	600	Short lengths	None

Table III
TENSILE TEST RESULTS

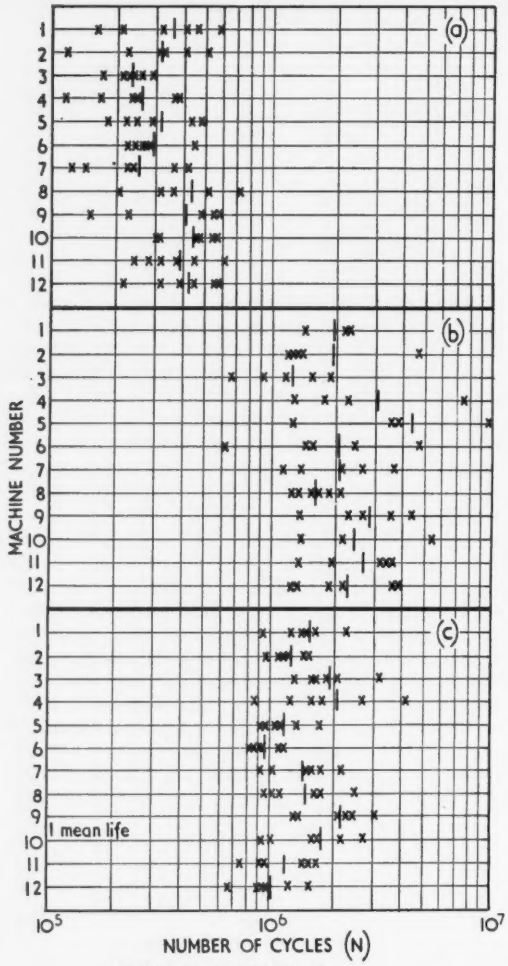
Bar Numbers	No. of Tests	Yield Stress, tons/sq. in. (mean)	U.T.S., tons/sq. in. (mean)	Elongation on 2-in. Gauge Length (mean), %	Reduction in Area (mean), %
1–8	16	20·2	33·5	36·3	60·2
9–29	30	20·4	31·5	38·2	60·0
30–50	18	20·6	30·5	39·3	61·9

Machining of the test pieces was performed in all cases on material in the final heat-treated condition. The test pieces were turned in a robust lathe between centres, the final critical section being machined with a single-point tool mounted in a specially constructed radius attachment. The critical section was polished by hand, first circumferentially to obtain dimensional accuracy, and then longitudinally to remove all tool marks and circumferential scratches which might act as potential stress raisers. Care was taken that no test piece varied in diameter by an amount greater than 0·0003 in. along the parallel portion as measured with a special micrometer fitted with knife-edge anvils and a fiducial indicator. In addition the test pieces were examined under a comparator microscope at a magnification of × 50 for potential stress raisers before being subjected to test.[8] During the period between polishing and testing, test pieces were stored in a desiccator cabinet, and, in the case of those to be tested in other laboratories, a coat of protective lacquer was applied before despatch. The final surface finish obtained was of a metallographic standard.

RESULTS

The results are presented in four sections, each describing separate investigations. The data from the first three experiments pose two problems to the statistician. One is that the distribution of fatigue life is skew. Many scientific workers studying fatigue from both practical and theoretical aspects have considered the logarithm of endurance instead of simply the endurance. Log life appears to be approximately ' normally ' distributed; the authors, following custom, have analysed logarithmically transformed data, and the consequent results are presented in this paper.

The other peculiarity of the data, characteristic of fatigue results, is incomplete information caused by the presence of unbroken test pieces. The authors believe that the endurance of many steels at particular stress levels may follow one of two distributions. The factors which determine the distribution for a particular test probably occur early in the life of the test piece. The authors intend to investigate these factors and have already started an initial pilot experiment. The experimental stress levels were chosen to avoid unbroken test pieces. However, owing to the unexpected variability of the testing material, a small proportion of test pieces from bars 9–29 revealed exceptional endurance when tested at ± 17·5 tons/sq. in. (similarly for bars 1–8, at ± 18·5 tons/sq. in.). The presence of the unbroken test pieces would invalidate the statistical analysis adopted in this



(*a*) Stress level ± 20 tons/sq. in.
(*b*) Stress level ± 18·5 tons/sq. in.
(*c*) Stress level ± 17·5 tons/sq. in.

Fig. 2—Comparison of machines (laboratory *T*): fatigue test results (excluding unbroken test pieces)

paper. But these exceptional results are not primarily due to the machine or laboratory in which they are tested; probably the same proportion would have arisen if all tests had been carried out on one machine; and for these reasons the results quoted in this paper exclude unbroken test pieces.

The significance tests used in the analysis of the experiments are described by Brownlee.[9]

Variation in Results from Similar Machines in One Laboratory

This experiment was carried out in the B.I.S.R.A. laboratory (*T*). The planned programme was to test six test pieces at each of two stress levels in each of 12 machines, and record the number of cycles to failure for each test. These 144 test pieces were chosen from bars 1–8, heat-treated as indicated in Table II. The test pieces were randomly allocated between the 12 machines. Stress levels of ±20 and ±18·5 tons/sq. in. were chosen on the basis of a conventional *S*/*N* diagram, previously determined, which indicated that the fatigue limit was of the order of ± 18 tons/sq. in. Because of variability displayed by individual test pieces the results of this experiment were not conclusive. Thus it was necessary to carry out a further 72 tests with test pieces prepared under closer control. The material was selected from bars 35–38, which had a rather lower tensile strength. An *S*/*N* determination had shown that the fatigue limit from these bars was ±16·5 tons/sq. in. It was therefore possible to carry out the series of tests, using six test pieces per machine at a stress level of ±17·5 tons/sq. in.

Altogether, each of the 12 machines produced a set of up to six results at each of the three stress levels, and these results are shown in Fig. 2. At any one stress level, therefore, there are 12 separate estimates of the mean number of cycles to failure, and these 12 estimates (each the mean of a set) are naturally not all exactly the same. The problem is to decide how likely it is that this degree of variability would arise as a result of variations from test piece to test piece if the entire programme had been carried out on one machine. If this is shown to be very improbable it is reasonable to assume that one or more of the machines has been behaving differently from the others.

In ' analysis of variance ' terminology, the variance of the whole series of results at one stress level from all twelve machines can be divided into two components:

(i) ' Between machines ' variance
(ii) ' Within machine ' variance.

The latter is a measure of the residual variability of the observations that cannot be accounted for on the hypothesis that each machine has some systematic bias affecting all the tests made on that machine. From the size of the ratio of the ' between machines '

Table IV

COMPARISON OF MACHINES: ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	Variance
	At stress level ± 20 tons/sq. in.	
Between machines	11	0·05427
Within machines	58	0·03232
Total	69	
Variance ratio = 1·68 (non-significant, $p > 0·05$)		
	At stress level ± 18·5 tons/sq. in.	
Between machines	11	0·08107
Within machines	44	0·05586
Total	55	
Variance ratio = 1·45 (non-significant, $p \simeq 0·20$)		
	At stress level ± 17·5 tons/sq. in.	
Between machines	11	0·06481
Within machines	60	0·01997
Total	71	
Variance ratio = 3·25 (significant, $p < 0·01$)		

variance to the 'within machine' variance, the required probability can be estimated, provided that the basic distribution is approximately normal and the individual machine variances are all the same order of size; i.e. no machine must have produced much more (or much less) variable results than the others. These two conditions were found to be satisfied after the data had been transformed logarithmically. In fact, the results from each of the three stress levels revealed no significant difference between the individual machine variances (although they did differ between stress levels). The analysis of variance for each stress level is detailed in Table IV.

The 'between machines' variances at the three stress levels, though not all alike, do not differ significantly; the 'within machine' variance at $\pm$ 17·5 tons/sq. in. is, however, significantly lower than at the other two stress levels. In fact, for stress levels $\pm$ 18·5 and $\pm$ 20 tons/sq. in. the 'within machine' variances are so large that only very marked differences between machines could have been detected. On the basis of these two results alone no evidence of significant differences between machine means exists.

However, under the more closely controlled conditions associated with tests at the $\pm$ 17·5 tons/sq. in. stress level, the conclusion is that there are significant differences between the mean lives obtained with the different machines. This conclusion, although it differs from that reached on results from the first two stress levels alone, is not a contradiction. It seems likely that if the tests at $\pm$ 20 and $\pm$ 18·5 tons/sq. in. were repeated, with the improved techniques used in preparation of test pieces, the results would confirm the $\pm$ 17·5 tons/sq. in. experiment.

Now, the expected values of the 'within machine' variance and the 'between machines' variance are:

$$\sigma_1^2 \text{ and } \sigma_1^2 + 6\,\sigma_2^2, \text{ respectively.}$$

σ_1^2 measuring the variation due to the test pieces, and σ_2^2 measuring the variation due to machines alone. Hence at $\pm$ 17·5 tons/sq. in. the estimate of σ_1^2 is 0·01997 and the estimate of σ_2^2 is 0·00747 ($= 37\%\ \sigma_1^2$).

It might be supposed that if the machines (or some of them) produce different results they do so systematically; e.g. that a test piece tested on a particular machine will *a priori* have a longer life than if it were tested on some other machine. No such consistent ranking of the machines occurred in these trials, either in respect of the mean number of cycles to failure or in respect of variance. When the machines are ranked in ascending order of mean cycles to failure there is no apparent consistency:

$\pm$ 20 tons/sq. in.	3	7	4	6	5	2	1	11	9	12	8	10
$\pm$ 18·5 tons/sq. in.	3	8	2	1	6	7	12	11	10	9	4	5
$\pm$ 17·5 tons/sq. in.	6	12	5	11	2	7	8	1	10	3	4	9

Test Piece Design

If results from different laboratories are to be compared, or if a particular conclusion of one laboratory is to be confirmed by another, when each used test pieces of different design, it is important that the differences, if any, in fatigue properties between the designs be known. To examine the differences between results from various test piece designs a limited

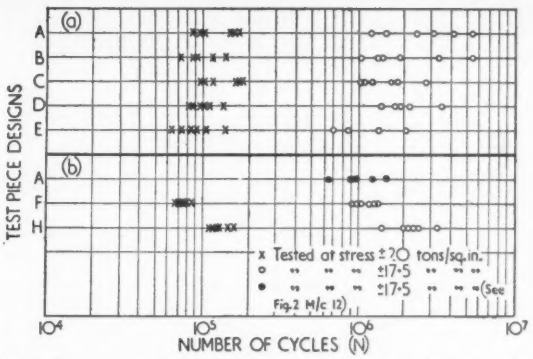


Fig. 3—Comparison of test piece designs: fatigue test results (excluding unbroken test pieces)

experiment was devised and performed entirely on a single machine in the B.I.S.R.A. laboratory (*T*).

The experiment was planned to compare five different designs of test pieces, namely designs *A*, *B*, *C*, *D*, and *E* (*see* Fig. 1). Pieces to design *G* could not be included, being suitable only for machines of the four-point loading type. Twelve test pieces of each design were prepared as previously described, from material chosen from bars 9–29. The test pieces were chosen randomly from that group of bars. For each design, six test pieces were subjected to a stress of $\pm$ 20 tons/sq. in. and six to $\pm$ 17·5 tons/sq. in.

The fatigue test results are shown in Fig. 3*a* for each stress level and for each test piece design.

The results were first examined to see whether any particular test piece design produced much more or much less variable results than the others. The variances, when calculated for each different design, were found to be homogeneous at both stress levels. However, when the five designs are arranged in order of decreasing variance, it can be seen that types *B* and *A* have relatively high variances, whereas *D* has a relatively low variance. This is true at both stress levels:

$\pm$ 20 tons/sq. in.	*B*	*A*	*C*	*E*	*D*
$\pm$ 17·5 tons/sq. in.	*B*	*A*	*E*	*C*	*D*

Furthermore, no significant differences were found to exist between the mean lives of the different designs at either stress level, and there is little evidence of consistency at the stress levels, as can be seen by examining the test piece designs ranked in decreasing order of mean number of cycles to failure, although *A*, *B*, *D*, and *E* retain the same order:

$\pm$ 20 tons/sq. in.	*C*	*A*	*B*	*D*	*E*
$\pm$ 17·5 tons/sq. in.	*A*	*B*	*D*	*C*	*E*

A similar though smaller experiment was also carried out to determine the effect of making modifications to test pieces of design *A*. The results of this are shown in Fig. 3*b*. In one case the test pieces were tested whilst covered with a plastic coating, identified as design *H*, and also a series of tests were performed using test piece design *F*, a development from design (*see* Fig. 1). Unfortunately, these test pieces had to be prepared from material chosen from bars 31–40, which is known to exhibit slightly different properties to material chosen from bars 9–20 (*see* Table III). Consequently, the results from these tests could not

Table V

FATIGUE STATISTICS FOR LOGARITHM OF NUMBER OF CYCLES TO FAILURE

Laboratories *T* and *U*

Laboratory Machine No.	Specimen Design	Stress Level			
		± 17·5 tons/sq. in.		± 20 tons/sq. in.	
		Mean	Variance	Mean	Variance
T3	A	6·16	0·0382	5·09	0·0222
T6	A	6·19	0·0195	4·99	0·0235
T8	A	6·21	0·0149	5·05	0·0158
T10	A	6·28	0·0320	5·19	0·0133
U13	A	6·14	0·0191	5·33	0·0064
U14	A	6·38	0·0124	5·42	0·0128
U15	A	6·17	0·0229	5·17	0·0223
U16	A	6·35	0·0453	5·48	0·0057

be compared directly with the results from the experiment previously described in this section. It is, however, possible to compare the results at the lower stress level with the results obtained from the earlier experiment (*see* preceding section).

It was found that the plastic coat had no appreciable effect on the fatigue results. There was, however, evidence that although the mean life of design *F* was the same as for design *A* the variability of the results had been reduced.

Test pieces of design *F* have been adopted as standard in the B.I.S.R.A. laboratory for future investigations. This decision was influenced not only by the above results, but also by the fact that test pieces of design *A* were found to fail as a result of fretting corrosion at a loading bearing when materials of high strength were tested.

Variability between Laboratories

This investigation was designed to compare seven different laboratories (*see* Table I) using the same experimental method as described in the preceding two sections. Six fatigue tests were attempted at each of two stress levels, ± 20 and ± 17·5 tons/sq. in., in each individual machine in each laboratory. The material was chosen from bars 9–29. Test pieces were prepared in laboratory *T*, as previously described; no work on the test pieces was required from the co-operating laboratories beyond the removal of a protective coating by means of a solvent.

Test pieces were allocated at random to every machine within each laboratory, i.e. no laboratory or machine was required to test material exclusively from one original bar. The test piece design tested in any laboratory was in each case the design normally utilized by that laboratory; in fact, no laboratory other than that of B.I.S.R.A. (*T*) was asked at any time to test pieces of a design other than their own. Four machines from the B.I.S.R.A. laboratory were included in this survey, tests additional to those already discussed being made.

The results from the experiment described in the preceding section have been used as a control in the analysis of the results provided by the different laboratories.

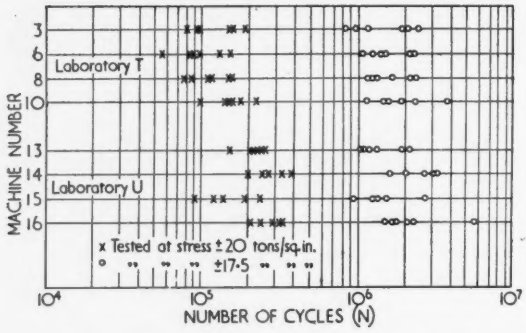


Fig. 4—Comparison between laboratories *T* and *U*: fatigue test results (excluding unbroken test pieces)

Table VI

FATIGUE STATISTICS FOR LOGARITHMS OF NUMBER OF CYCLES TO FAILURE

Laboratories *T*, *V*, *W*, *Y*, *Z*

Laboratory Machine No.	Specimen Design	Stress Level			
		± 17·5 tons/sq. in.		± 20 tons/sq. in.	
		Mean	Variance	Mean	Variance
T 12	B	6·32	0·0729	5·06	0·0249
V 17	B	6·34	0·0407	5·32*	0·0199
V 18	B	6·36	0·0388	5·36*	0·0361
T 12	C	6·17	0·0258	5·13	0·0146
W19	C	6·06	0·0136	5·24	0·0299
W20	C	6·30	0·2435*	5·06	0·0175
T 12	D	6·31	0·0197	5·00	0·0068
Y 23	D	6·30	0·0232	5·30*	0·0213
Y 24	D	...	...	...	...
Y 25	D	6·74	0·2330*	5·49*	0·0151
T 12	E	6·06	0·0420	4·96	0·0145
Z 26	E	6·41	...	4·89	0·0016*
Z 27	E	5·87	0·0225	4·89	0·0063
Z 28	E	6·22	0·0320	4·88	0·0034
Z 29	E	5·85	0·0311	4·93	0·0152
Z 30	E	5·96	...	...	...
Z 31	E	6·16	0·0232	4·92	0·0040

* These results differ significantly from the comparable results obtained from laboratory *T*.

Table VII

FATIGUE STATISTICS FOR LOGARITHM OF NUMBER OF CYCLES TO FAILURE

Laboratory *X*

Laboratory Machine No.	Specimen Design	Stress Level			
		± 17·5 tons/sq. in.		± 20 tons/sq. in.	
		Mean	Variance	Mean	Variance
X 21	G	5·68	0·1601	5·37	0·1456
X 22	G	5·57	0·0150	5·04	0·0417

Laboratory *U* is equipped with four fatigue-testing machines which handle test pieces of design *A*; the additional tests in the four machines in laboratory *T* used the same test piece, and a direct comparison can be made between the laboratories. Evidence of a difference between them exists (*see* Fig. 4). The difference between the mean lives of test pieces tested in laboratory *U* and those tested in laboratory *T* is very pronounced at the ± 20 tons/sq. in. stress level. The 'within machine' variability is comparable for the eight machines in the two laboratories. However, the machine-to-machine variability of laboratory *U* is significantly higher than for laboratory *T* (Table V demonstrates these results).

No other laboratory can be compared with laboratory *T* on such a balanced and comprehensive scale, and so results quoted for other laboratories must be more tentative. Figure 5 shows the test results provided by the other laboratories and Table VI summarizes the fatigue statistics.

Laboratory *X* uses test pieces of design *G* for fatigue experiments. This design of test piece could not be tested in laboratory *T*, so that laboratories *X* and *T* cannot be directly compared. However, large differences certainly exist between the results from laboratory *X* and from other laboratories, as can be seen from Fig. 5 and from Table VII, but whether these differences are due to the type of test, the design of test piece, laboratory variability, or any combination of these, it is not possible to decide.

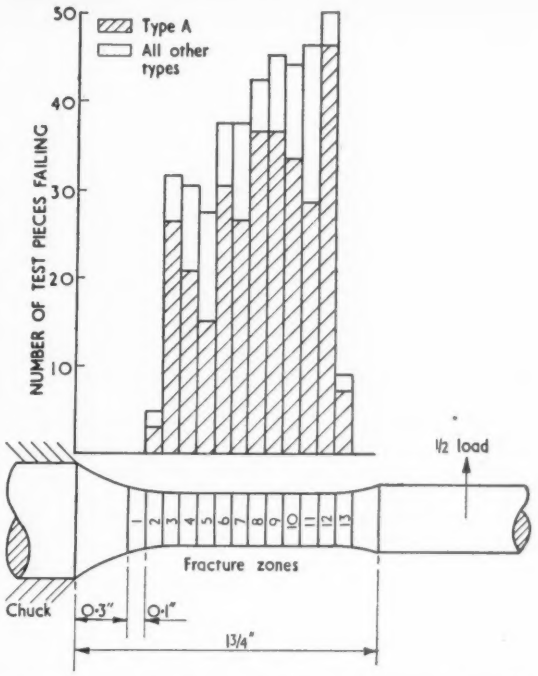


Fig. 6—Incidence of fatigue failures in specified fracture zones

Position of Fracture

Under the condition of constant bending moment, which is assumed to exist with a two-point loading

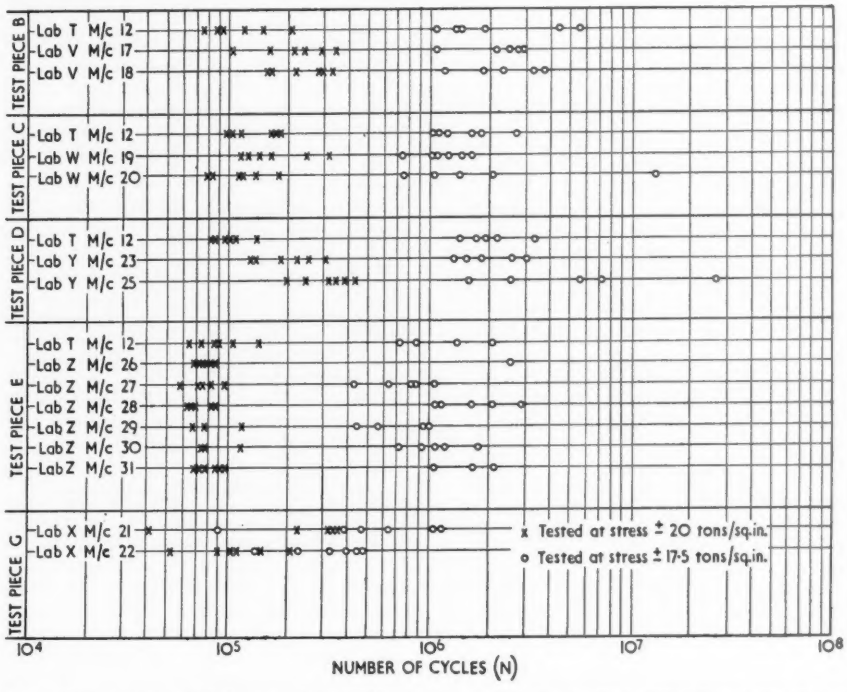


Fig. 5—Comparison of laboratories: fatigue test results (excluding unbroken test pieces)

Wöhler test, there should be an equal change of failure occurring at any position along the parallel portion of the test piece, provided that no mechanical notch or metallurgical effect is present. If the position of failure along the critical section is recorded for a large number of tests and the distribution of these positions is analysed it should be possible to decide whether in fact the condition of constant stress is achieved.

To permit a record to be kept of the position of fracture, the critical section was imagined to be split into 13 zones of equal width from the chuck end, as shown in Fig. 6. Data in respect of the zone in which a test piece fractured were recorded for about 450 of the 600 or more tested. The distribution of the number of test pieces failing in each zone is shown in Fig. 6. There is a tendency for more pieces to fail in the zones 8–12 than in the zones nearer the gripped end of the test piece. An increase in the magnitude of one of the two loads would obviously affect the form of bending moment imposed on the test piece, and if the difference between the loads took the form of a slight increase in the upward force, an increase in the number of fractures occurring in the zones furthest from the chuck end could be expected. A careful check of the testing machines in the B.I.S.R.A. laboratory, however, failed to indicate any disparity, and in any case the same error could not be expected from all 12 machines since they were individually built. One other factor which could unduly affect the position of failure in the test piece—any tendency towards undercutting at the point of transition from parallel into the radius—would increase the stress concentration at that point and in consequence increase the chance of failure there. Although very great care was taken in test piece preparation, this second factor cannot entirely be ruled out as the cause of the predominance of failures occurring in zones 11 and 12.

DISCUSSION AND CONCLUSIONS

The primary object of the investigation was to determine whether the equipment and techniques adopted by the B.I.S.R.A. laboratory could obtain results which were not only reproducible but which also lay within narrow limits of variability. If these limits are too wide, the influence on fatigue properties of metallurgical conditions being investigated may not be apparent. The conclusions are stated only for the particular steel being tested and for the stress levels considered.

During the experiments the importance of having a consistently high standard of test piece preparation was emphasized. Difficulty was experienced in attempting to produce the large number of nearly identical test pieces required for the experiment and yet still keeping the high standard of finish for each test piece. Satisfactory methods were not achieved at once, but techniques were found to ensure that the variation in results, from test piece to test piece, was kept small. A standard has now been established which will be used in all future experiments.

The experiments revealed that no large differences existed between the results of tests made under identical conditions. However, significant differences were observed between results from different testing machines. There is no evidence of any systematic machine bias, and the results should be interpreted as simply meaning that in a single experiment where more than one machine is used the results will be more variable than if only one machine were employed. When En.4 steel is tested at $\pm$ 17·5 tons/sq. in. the variability is increased by 37%.

The scatter of results obtained from each different design of test piece, which had a common critical section, was found to be very similar, and there were no differences between the lives of the test pieces for the designs. An attempt was made to reduce the variability shown when design *A* was tested in the B.I.S.R.A. laboratory. It was suspected that one of the causes of this variation was insecure gripping of the test piece by the loading bearings. This wandering of the loading bearings resulted in a variation of the applied moment. Design *F* should not suffer from this fault and it would be expected that test pieces of this design would yield less scattered results than those of design *A*; this was confirmed by experiment.

The conclusions to be drawn from the results obtained from the co-operating laboratories are similar to those already stated about the machine differences. Significant differences between the results provided by the different laboratories have been shown to exist. The machine-to-machine variability in most of the laboratories was found to be as high as, if not higher than, that in the B.I.S.R.A. laboratory.

Comparison of the results produced by testing machines of the four-point loading type with those produced by machines of the two-point loading type shows that they differ markedly. The limited scope of the present investigation does not permit an assessment of the testing machines alone, since various other factors may have contributed to the difference. The results, however, are of interest and it may be that further investigation is worth consideration.

The results in general indicate that if it were possible to prepare completely identical test pieces and the tests were repeated, the results from any one machine, with one or two possible exceptions, would be practically the same. This would not be so, however, from machine to machine, and differences would be even more pronounced from laboratory to laboratory.

Some precision has been lost in the experiment owing to the unexpected variability in material. Practically a whole ingot has been used during these experiments, and a trend in metallurgical properties through the ingot has been detected. It would seem desirable to enquire further into the influence of ingot structure on mechanical properties (in particular the fatigue properties) of wrought steel.

Acknowledgments

The authors gratefully acknowledge the co-operation of the six laboratories concerned in these experiments. The encouragement given by the Fatigue and Inclusions Committee, of which Dr. H. H. Burton is Chairman, has been most gratifying and their valuable discussions of the work are much appreciated. Particular mention should be made of the considerable assistance rendered by the N.P.L. and M.E.R.L. (Mr. C. E. Phillips), The Bristol Aeroplane Co., Ltd.

(Mr. P. H. Frith), and the R.A.E., Farnborough, during the formative days of the B.I.S.R.A. Fatigue Laboratory.

References

1. E. EPREMIAN and R. F. MEHL: "Investigation of the Statistical Nature of Fatigue Properties," Technical Note 2719: 1952, National Advisory Committee for Aeronautics.
2. E. EPREMIAN and R. F. MEHL: "The Statistical Behaviour of Fatigue Properties and the Influence of Metallurgical Factors," Special Technical Publication 137: 1952, Philadelphia, American Society for Testing Materials.
3. A. M. FREUDENTHAL and E. J. GUMBEL: *Proc. Roy. Soc.*, 1953, vol. 216, ser. A, pp. 309–332.
4. W. WEIBULL: *J. Appl. Mech.*, 1952, vol. 19, pp. 109–113.
5. J. CLAYTON-CAVE: To be published.
6. C. E. PHILLIPS: Aeronautical Research Committee, Paper No. 7128, 1948.
7. "Manual on Fatigue Testing," p. 7, Special Technical Publication 91: 1949, Philadelphia, American Society for Testing Materials.
8. J. CLAYTON-CAVE and E. INESON: *Metal Treatment*, 1953, vol. 20, pp. 553–556.
9. H. A. BROWNLEE: "Industrial Experimentation": 1949, London, H.M.S.O.

APPENDIX

Natural Resonance Frequencies

In carrying out fatigue tests in machines based on the Wöhler design, it is important that superimposed stresses due to vibration should be minimized by operating at frequencies well clear of natural resonance frequencies. The latter were explored in the B.I.S.R.A. laboratory at two stress levels with a Giesler vibrometer over the total range of speeds of which the machines were capable. Measurements of amplitude were made at the outer loading shackle. A lower applied stress of $\pm 17{\cdot}5$ tons/sq. in. was obtained with test pieces machined from the same batch of mild-steel as that used for the whole investigation. A higher applied stress of ± 30 tons/sq. in. was also investigated using an alloy steel to B.S. 970 specification En. 18, hardened and tempered to 60 tons/sq. in. It was observed that at $\pm 17{\cdot}5$ tons/sq. in. distinct peaks occurred at speeds of rotation of approximately 1000 and 3000 r.p.m., whilst the minimum value is in the region of 5000 r.p.m. or above. At a stress of ± 30 tons/sq. in. major resonance peaks were obtained at similar positions to the lower stress tests, but in addition some smaller peaks were obtained, notably at frequencies of 500 and 1600 r.p.m. It is clear that in the range investigated the amplitudes of vibration are at a minimum at frequences of about 2400 and beyond 5000 r.p.m.

In the interests of obtaining data as quickly as possible the higher frequency of 5000 r.p.m. has been adopted in the B.I.S.R.A. laboratory for all experiments. The amplitude of vibrations appears to be affected by either the type of material under test or the stress level being used, or even both, and checks are advisable when either of these factors is changed.

Training in the Iron and Steel Industry

By A. W. W. Watson

SYNOPSIS

After analysing the factors which have controlled the development of training in the iron and steel industry, the paper describes the structure of the industry's training organization. Developments since the war are briefly outlined with particular reference to co-operative activities which have been undertaken both regionally and nationally as a service to the industry. 1135

THE INCREASED ATTENTION paid to training since the second World War is not confined to the iron and steel industry. Nor has it been restricted to any single grade of worker or occupation. Over the last ten years there has been a growing tendency throughout industry to put training for manual workers, staff, and management on a systematic basis.

There are a number of reasons for this trend. Technological changes bringing the introduction of new plant of increasing size and complexity, full employment (and a consequent shortage of labour), and economic factors demanding an increase in production with the minimum of production costs have all combined to create a situation in which traditional and informal methods of training are no longer sufficient. The iron and steel industry has been affected by these factors to a greater extent than many other industries. Since the war, for example, the industry has spent £400 million on modernization, and at the present time is continuing to spend about £1 million a week. It is estimated that about £6000 worth of plant and equipment are needed for every worker employed, and it is clearly essential that this equipment should be operated safely, efficiently, and to maximum capacity. Furthermore, the growth of light industry in many of the iron and steelmaking areas has tended to attract labour away from heavy industry where shift working is the rule and where, in some departments, the work is hot and heavy.

Over recent years the development of training in the iron and steel industry has been conditioned by a number of factors. Some of these are common to all industries in the U.K., while others apply particularly

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to the iron and steel industry, because of the nature of the processes and the organization of work.

FACTORS CONTROLLING THE PATTERN OF TRAINING

Of the general factors which affect the training of workers in all industries, the most important are the changes in the country's educational system, National Service, and full employment. The raising of the school-leaving age and the provision of more facilities and incentives for young people to continue their education beyond this age have materially reduced the supply of juvenile labour of the type from which industry has traditionally drawn most of its recruits. This has aggravated the problems arising from the general shortage of young workers which is the result of a decline in the birthrate during the years preceding the war. More boys are continuing their education to the age of 18, and since the war the numbers attending universities have increased from about 50,000 to between 80,000 and 90,000. Although this is undoubtedly to the benefit of the nation as a whole, it has affected training in so far as schemes for the training of young workers must be sufficiently flexible to allow for the recruitment of boys at any age over 15.

The period of National Service, extending over two years, affects both the recruitment of boys and the duration and pattern of training schemes devised for them. Boys who continue their secondary education to the age of 18 or over have normally to complete National Service before entering industry. On the other hand, the training of those leaving school at 15 or 16 must either be completed before they are called up for National Service or planned to allow for an interruption lasting two years.

Full employment and the fact that throughout industry generally there are more jobs than there are workers to fill them has resulted in a greater mobility of labour, which inevitably complicates the introduction and running of planned comprehensive training schemes. There has been an increased temptation also for boys to seek the easiest and most remunerative jobs rather than to undertake systematic training, which usually involves discipline and study and very often the acceptance initially of a lower rate of pay while under instruction, although their prospects ultimately would be improved.

FACTORS AFFECTING THE IRON AND STEEL INDUSTRY

Other factors which have controlled the development of training in the iron and steel industry are inherent in the structure of the industry and the nature of its processes. In the first place there is the wide range in the size of individual companies and the very great variety of their products. The British Iron and Steel Federation has some 350 member companies, all of which are engaged in one or more processes in the manufacture of iron and crude steel or in its hot or cold working. The largest of these companies employ many thousands of workers, and at the opposite end of the scale there are many small companies employing less than a hundred. This variation in size of company and product and the large number of trades and occupations which can be found even in a single steelworks make it impossible to lay down any rigid formal schemes of training for the industry as a whole.

In most of the production departments of the industry workers are employed in teams, a continuous shift system is operated, and promotion is largely governed by seniority. This raises special training problems, particularly in the case of young operatives who have traditionally taken their place in a team at the age of 16. Once an operative is working in a team it is difficult to arrange release for him from his duties for further training, and shift work makes it even more difficult for him to follow a regular course of part-time study.

In addition to production workers there are a very large number of men employed to provide the maintenance services which are essential in a steelworks. Most of these (e.g. fitters, electricians, and bricklayers) belong to one of the craft trades. As such they serve an apprenticeship and any training planned for them is controlled by the length of this apprenticeship, the age limit for entry, and other conditions laid down by agreement between the unions and employers. The existence of these conditions and their effect on the training of young workers is often overlooked, particularly in those countries where there are no craft unions.

As an indication of the magnitude of the problem it should be mentioned that the training arrangements for the iron and steel industry cover in all about 270,000 workers, of whom about 22,000 are young persons under the age of 21. These young workers may conveniently be divided into four groups: young workers in production departments, who are normally known as junior operatives; craft apprentices; technical apprentices; and clerical workers. The junior operatives form the largest group, numbering about half of all junior workers.

THE DEVELOPMENT OF TRAINING

The traditional method of training in the iron and steel industry, as in other industries, has been instruction on the shop floor by example and practice. There is no doubt that this is a well tried method which has served the industry well from the earliest times through the industrial revolution to the present day. Although practical instruction on the job remains the basis of all vocational training, it is no longer sufficient by itself to provide the industry with the skilled labour force required in the conditions existing today.

Some of the reasons for this have already been mentioned. One of the most important is the changing pattern of skills in the industry, particularly in production departments, following technological changes. Increasing mechanization and the installation of large units of equipment have greatly lessened the amount of physical effort required in, for example, rolling mills. On the other hand, a mistake can lead to loss of production and damage to plant on a much larger scale than in the past. For this reason it is essential to have operatives trained to a high degree of efficiency.

In addition to this operating skill it is generally agreed that workers should know something of the principles on which the processes are based. Similarly, they should understand how their particular job fits into the process as a whole—the work of the

department, the company, and the industry. This knowledge and appreciation should encourage them to take an active and intelligent interest in their work, particularly in large integrated steelworks and in those departments where the process is continuous and largely automatic.

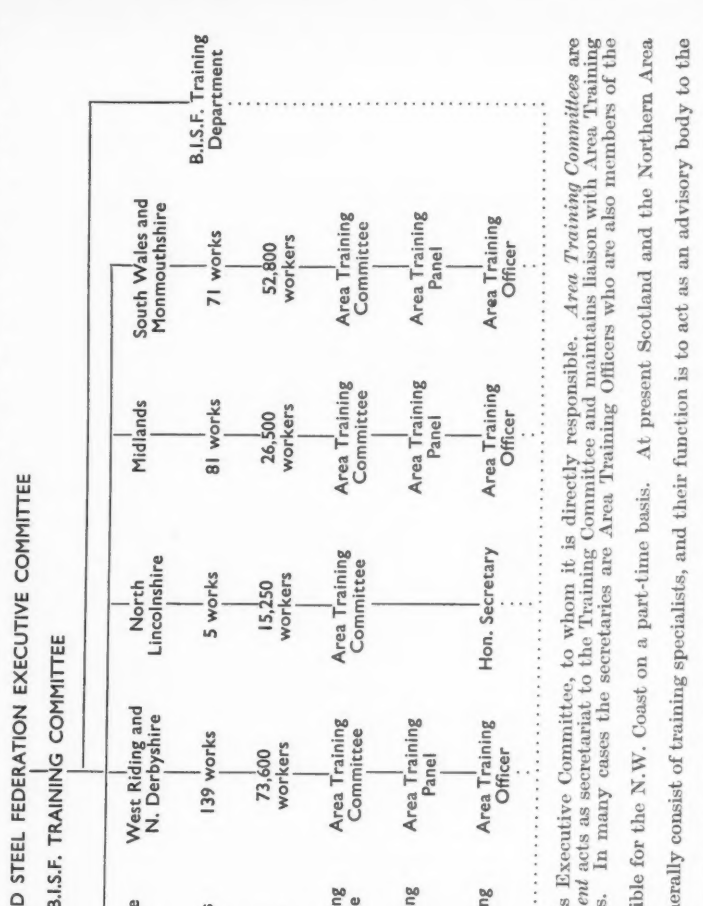
The need to establish training schemes which can provide both operational skill and background knowledge for all grades of worker has been appreciated in the industry for many years. It is realized that the greater part of this training must be given in the department in which the trainee is working and is the responsibility of the manager and supervisor under whom he is placed. At the same time there are advantages to be gained by organizing trainees in groups and arranging courses for them, particularly in certain specialized aspects of their work. In this way it is possible to ensure a uniformly high standard of instruction and simultaneously to save the time of production staff.

Larger companies usually have a sufficient number of trainees to organize a great deal of their training, on this basis. Most of them employ full-time training staff and provide centres or similar premises where this training can be carried out. In small companies the management is able through personal knowledge to study the progress of every employee and for this reason it is easier for them to provide training on an individual basis. On the other hand, because they seldom have a sufficient number of trainees for any single trade or occupation, it is difficult for smaller companies to arrange formal training courses, except on a co-operative basis with other companies.

TRAINING ON AN INDUSTRY BASIS

In the iron and steel industry co-operative action in the field of training was started in 1948 and training on an industry basis has been developing ever since.

Two of the functions of the British Iron and Steel Federation are the provision of common services, which it would be uneconomic or impossible for companies



1. The *Training Committee* is appointed by the Federation's Executive Committee, to whom it is directly responsible. *Area Training Committees* are responsible to the Training Committee. The *Training Department* acts as secretariat to the Training Committee and maintains liaison with Area Training Committees, mainly through the secretaries of these committees. In many cases the secretaries are Area Training Officers who are also members of the Training Department.
2. The Area Training Officer for Lancashire is also responsible for the N.W. Coast on a part-time basis. At present Scotland and the Northern Area are served by the same Area Training Officer.
3. Whilst their composition varies, *Area Training Panels* generally consist of training specialists, and their function is to act as an advisory body to the Area Training Committee.

Fig. 1—Organization of training in the iron and steel industry

to provide for themselves, and arranging for the pooling of knowledge for the industry as a whole. In 1948 the Federation appointed a Training Committee consisting of directors, works executives, and training officers from member companies to arrange for these functions to be fulfilled as far as training was concerned.

In each of the eight main steelmaking districts an Area Committee was established and in the six largest areas the Federation has appointed Area Training Officers who act as secretaries to the Committees. In London the Federation's Training Department acts as a secretariat to the main Training Committee and arranges courses and conferences planned by the Committee for the industry as a whole. Figure 1 illustrates the structure of the Area Training organization.

The purpose of the Federation's Training organization is to provide a service which will enable all companies, and particularly smaller companies, to get the benefit of the pooled experience of the whole industry. Conferences and meetings are held both regionally and nationally for the whole industry, and a wide range of publications and visual aids has been prepared for use in training. Co-operative training courses are arranged, some intended primarily for small and medium-sized companies and others in certain specialized subjects where even the largest companies are unable to muster sufficient trainees to warrant holding their own courses.

DEVELOPMENTS SINCE 1948

Since 1948 there have been many developments in the field of training in the iron and steel industry, and practically every category of trade or occupation has been affected to a greater or lesser extent. Training schemes and courses have been devised and put into operation both by individual companies and by the Federation's Training Committee for all grades from management to new employees.

Management Training

In the field of management training the years since the war have been very largely a period of experiment. Even the larger companies in the industry who have established schemes to train their future managers have been constantly examining and testing new techniques of selection and training.

There are two main reasons why the problem of ensuring an adequate supply of competent managers has assumed a special importance. In the first place, technological developments in the industry are tending to make more exacting demands upon a manager's ability. As works and departments become larger, problems of administration and labour relations become more complex and a wrong decision becomes more costly. A relatively small error of judgment in one department can seriously affect a whole works.

The second reason will be found in the effects of developments in education since the war. At one time, the majority of the managers in the iron and steel industry were found among the ranks of boys who joined the industry straight from school at an early age. But the effects of the 1944 Education Act, which aimed at providing secondary and university education for all with the necessary ability, irrespective of means, are now being felt. The number of boys qualified by intelligence who do not continue their education till the age of 16, 18, and even 21 is becoming increasingly small. As a result the industry is being forced more and more to look to the grammar schools, the public schools, and the Universities for a larger proportion of its managerial recruits.

The result of these changes, combined with the period of National Service, is that many companies are recruiting trainees for management at the age of 20 or 23, to occupy positions which not many years ago would have been given to men with six to nine years' experience in the industry. The training of these recruits must clearly be planned to take advantage of their continued education while widening their experience in as short a time as possible.

Almost all the large companies have established formal schemes to train their future managers. In many cases they supplement this training by sending trainees on courses run by technical colleges and universities and by using the exchange scheme organized by the Federation whereby about 70 young executives are sent abroad every year for a month's visit to iron and steel companies in Europe. In addition to this, two or three of the largest companies have conducted regular courses of residential training for their managers.

This last development is clearly impossible for the medium and small company, and so Area Training Committees have accepted the responsibility for undertaking this work. One of the advantages of this type of course over those provided by outside bodies is that the subjects studied can be related directly to the iron and steel industry. A feature of these courses is the time spent in syndicates studying problems such as plant reorganization, accident prevention, costs, and labour relations. Speakers on these courses are almost always managers from the industry with wide practical experience of their subject.

In addition the Federation's Training Committee appointed an *ad hoc* Sub-Committee to study training and education for management in the industry. The report of this Sub-Committee, which was approved by the Federation's Executive Committee, has recently been published. Among the recommendations embodied in the report is a suggestion that experimental courses for managers from the industry should be organized by the Federation on a national basis.

Foreman Training

For many years the accepted method of training foremen in the industry has been personal instruction under the manager immediately above him. This system still remains the basis of foreman training but, as with managers, more and more it is being supplemented by formal courses and schemes. These may take the form of part-time courses held over a period, regular meetings, or short residential courses (Fig. 2). To help the medium-sized and smaller companies residential courses lasting about a week are also being organized regularly by Area Training Committees in five areas. Up to the end of 1954 a total of over 1600 foremen from 150 companies had attended such courses.

A more recent development has been the holding of specialized courses for foremen from similar depart-

ments in different companies such as open-hearth melting shops, rolling mills, or forges. These courses are still very largely experimental but this would appear to be an extremely appropriate field for co-operative action, since even the largest companies could scarcely release a sufficient number of foremen from any one department to justify holding such a course. One of the most striking features of these courses has been the practical nature of the discussions. Many of the foremen attending have previously been on general courses and it seems that specialized courses are a most effective form of 'follow-up' to these.

The provision of suitable 'follow-up' training, which is generally regarded as being essential if the effects of the residential course are to be maintained, is a most difficult problem. Companies are tackling this problem in a variety of ways, and one which has proved most effective has been the establishment of foremen's associations or clubs, run by the foremen themselves, for the arrangement of both social and educational activities. In addition some Area Training Committees hold general 'follow-up' courses or week-end conferences for foremen who have attended a general residential course. In Lancashire the Area Training Committee has arranged a scheme of 'follow-up' training consisting of evening lectures and meetings planned over three years.

In addition to courses designed specially for the industry many companies make use of courses in foremanship arranged by outside bodies and institutions. Similarly, many foremen study through technical colleges for the Certificate in Foremanship of the Institute of Industrial Administration. The Training Within Industry programmes of the Ministry of Labour are widely used.

Apprentice Training

A great number of craftsmen such as fitters, bricklayers, and electricians are required in the industry to maintain plant and equipment and provide essential services. The training of apprentices for these trades has been established for many years and virtually all companies have some formal training arrangement for them. The existence of a recognized period of apprenticeship provides an excellent opportunity of training apprentices along systematic lines, giving them instruction and practice in every aspect of their trade.

Fig. 2—Foremen at a residential course studying a model rolling mill

The type of training and the way in which it is given vary and courses are arranged to suit the needs of the company, giving the apprentice's instruction any bias which the company feels he will require. Many of the large companies have special training centres where the apprentice spends part of his time learning the use of appropriate hand and machine tools and the other skills of his trade. In smaller companies, where there are not sufficient apprentices to justify the provision of training centres or full-time instructors, instruction is usually arranged on an individual basis with as much variety of experience as the company can provide.

Because the training of apprentices is so well established, there have been few developments on a co-operative basis either regionally or nationally. The training of skilled instructors, however, has presented a problem in the past and for the last two years the Ministry of Labour, at the request of the Federation's Training Committee, has held courses for craft instructors in the iron and steel industry at its Technical Staff College in Letchworth. The courses, which have been found extremely effective, last for two weeks and give instruction and practice in teaching techniques.

Operative Training

Some of the difficulties which have to be faced when planning the training of operatives have already been indicated. For the most part they arise from the fact that many production processes are carried out by teams of men working on shifts and the fact that promotion in these teams is almost invariably by seniority. In spite of these difficulties many companies have established training schemes for operatives.

Introductory or initiation courses which give newcomers information about the structure, processes, and products of the company are now the rule rather than the exception for junior workers entering the industry. The courses are usually arranged at a time when there is an intake of juniors from school, and apprentices, clerical workers, and operatives often attend the same course. In many cases similar courses for new adult workers are also arranged.

If a boy enters the industry at the age of 15 it is possible to give him a year's general training with experience in a number of different departments. Since he will not be engaged on shift work as a member of a team, however, there is obviously a limit to the amount of practical instruction he can be given, and this period of training is more useful in giving him general background knowledge of the company and the industry as a whole. On reaching the age of 16 he is normally put on shift work as a member of a production team and this makes it difficult to continue further planned training for him without affecting the work

Fig. 3—A steelmaking film is screened for workers on the melting-shop floor

of the team. Possible solutions are the establishment of a pool of junior labour in the department or the employment of youths as supernumeraries, but there are practical difficulties in the way of these as well.

In spite of these obstacles companies in the industry are experimenting with various schemes of training for junior operatives. Many of them are putting their operatives through the Iron and Steel Operatives' Course of the City and Guilds of London Institute.

Iron and Steel Operatives' Course

The City and Guilds of London Institute first started this course shortly before the war. It is only in recent years, however, that the popularity of the course has spread. In addition to courses run in technical or county colleges, some companies hold courses in their works at which instruction is given by members of the staff. This is often a convenient arrangement, since by duplicating the lectures it is possible to cater for workers on shift. During the last three years between 1200 and 1300 people have taken the examination and many more times this number have taken the course without taking the examination.

To further interest in the operatives' course the Federation's Training Committee make a number of annual awards, in the form of medals, to the leading candidates in the examination. In 1954 a short conference was arranged for representatives of the City and Guilds and of education authorities together with instructors teaching the course and training officers. The purpose of the conference was to discuss the syllabus of the course, the examination, and the most suitable teaching methods for operatives who are not in general academically inclined. Partly as a result of this conference the syllabus of the course is to be revised and will consist of two sections. The first will provide a general survey of the industry and its processes as a whole. The second will enable the student to select a particular process for detailed study. A reasonably intelligent boy who attends classes for four hours a week should be able to complete the course in three years.

It has been found in some companies that adult workers are reluctant to take courses of study run on traditional lines, particularly if these involve regular attendance in the evenings over a long period.

For this reason a less formal method of training adult operatives in the latest techniques of their trade is now being experimented with by one or two companies. Meetings are held at regular intervals at which two or three short technical talks are given by members of the department concerned on different aspects of the subject under discussion. These are followed by periods of open discussion and it has been found that these meetings arouse great interest among the operatives. The manager of the department acts as chairman at the meetings, which are run on informal lines. This scheme is only one example of the many ways in which individual companies are trying to solve the problem of training their operatives.

Ancillary Workers

There are a great number of men employed in the industry operating ancillary processes essential to the running of a steelworks. Crane drivers, slingers, power plant operatives, locomotive drivers, and shunters are all examples of this type of worker. In almost every case it is essential that they should receive practical instruction in the techniques of their trade, and there has been a tendency in the larger companies to incorporate this instruction in planned training courses. The damage and loss of production which can be caused by an error of judgment on the part of, for example, a crane driver is readily apparent.

General Activities

Something has been said of the developments which have taken place over recent years in the training of various grades of worker. In addition there have been many activities not directly related to vocational or practical training which are nevertheless likely to prove of value to the industry as part of a long-term policy.

Pre-National Service courses for boys in the industry who are expecting call-up are examples of this type of activity. Their purpose is to give the boys general information about life in the armed forces and advice which will enable them to make the most of the opportunity which their period of National Service affords. Speakers are usually representatives of the Services and very often a visit to a military unit is arranged as part of the course. These courses are run regularly by many companies and also on a co-operative basis by Area Training Committees.

The relations between the industry and local Education Authorities is another field in which the Area Training Committees are able to do a great deal of valuable work. Conferences and meetings have been held to discuss matters of common interest and short courses have been arranged for schoolmasters, designed to give them information about the industry. The Federation's instructional publications and visual aids are made available to schools. In the same way the Area Training Committees keep in close touch with the local Youth Employment service.

The main Training Committee of the Federation has also been active in arranging conferences and courses on a national basis for the whole industry. Every year since 1948 an annual conference has been held at Ashorne Hill, Warwickshire, at which some

aspects of training in the industry have been discussed. In 1953 " Training and Education for Management " was the general theme of the Sixth Conference, and on this occasion 190 delegates, over 70 of whom were senior executives, attended representing companies in the industry, universities, and technical colleges. In 1954 the theme of the Conference was " Education and Training of Junior and Adult Operatives." Reports of these and earlier conferences are published and made available both inside and outside the industry.

Courses have also been arranged for training officers in the industry. These last ten days and are designed to give practical information primarily to members of smaller companies who are not training specialists, but combine this function with other responsibilities.

One of the most valuable services that the Federation's training organization is able to provide for member companies is the means of pooling and exchanging information. There are many ways in which this is done both locally and nationally. Three years ago a series of ten memoranda were prepared giving information about the development of training in the industry. These dealt with the training of various grades of worker, giving an indication of what companies were doing in each particular field and details of courses and facilities available outside. A small magazine is also published quarterly containing information on recent developments, news of company activities and articles on specialized aspects of training both in this country and abroad.

Publications and Visual Aids

To assist in training, a wide range of publications and visual aids has been produced by the Training Committee. Two booklets, twenty-one film-strips, and a set of wall-charts have been produced which illustrate all the main basic and finishing processes of iron and steel production. More recently nine instructional films, each lasting about 15 minutes, have been made (*see* Figs. 3 and 4) and three more are under production. All of these films, film-strips, wall-charts, and booklets have been designed as an integrated series. They are based primarily on the syllabus of the Iron and Steel Operatives' Course and are related directly to each other and to the text book, " The Manufacture of Iron and Steel,"* which was written and published specially for the course. Figure 5 shows how this series of visual aids and publications has been built up. The films are kept in a film library together with the other Federation films and copies may be borrowed free of charge or purchased at cost price by member companies. The work of supervising the production of these publications and visual aids is entrusted to two sub-committees of the Training Committee.

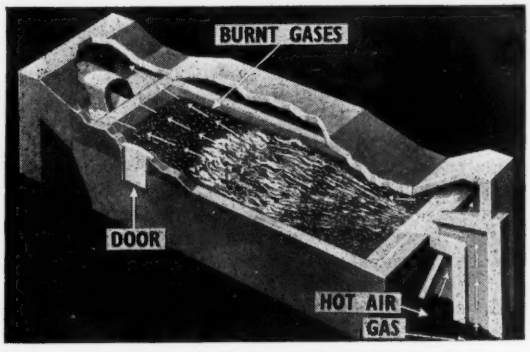


Fig. 4—Part of a diagrammatic sequence from the B.I.S.F. instructional film " The Open-Hearth Furnace "

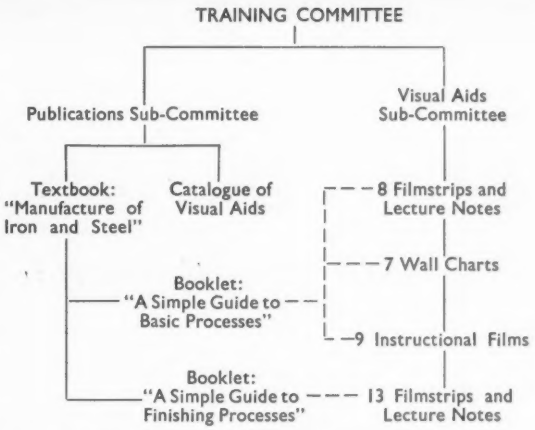

TRAINING COMMITTEE
Publications Sub-Committee
Visual Aids Sub-Committee
Textbook: "Manufacture of Iron and Steel"
Catalogue of Visual Aids
8 Filmstrips and Lecture Notes
7 Wall Charts
Booklet: "A Simple Guide to Basic Processes"
9 Instructional Films
Booklet: "A Simple Guide to Finishing Processes"
13 Filmstrips and Lecture Notes

Fig. 5—Chart showing the relationship between visual aids and training publications

CONCLUSION

This outline of the many developments which have taken place in recent years may give some indication of the pattern which training in the industry is tending to follow. Of the problems which had to be faced at the outset, some at least remain largely unsolved. A great deal of experimental work has already been done, and with the free exchange of information that exists between companies there would appear to be no reason why the obstacles should not be surmounted.

Owing to the wide range of processes covered in the industry and the varying size of the companies, it is not possible to lay down a comprehensive scheme of training for the whole industry. It is right and proper that individual companies should be responsible for framing their own schemes in the light of local conditions and to cater for their own needs. At the same time the services of the Federation's training organization are at their disposal should they require them. Despite variations in practice it can be said that no disagreement exists about the broad aims which training should seek to achieve.

A guide to these aims was given by Mr. A. G. Stewart, Chairman and General Managing Director of Stewarts and Lloyds, Ltd., and this year's President of the Federation, in a recent speech. Training, said Mr. Stewart, " could help to ensure that the best working methods were taught and used: by helping to ensure correct working it could help in ensuring safe working; lastly it could help to contribute to the effective use of labour by helping each man to develop himself to the limit of his natural abilities."

* D. J. O. Brandt, " The Manufacture of Iron and Steel ": 1953, London, English Universities Press.

The British Iron and Steel Research Association

THE LONDON GROUP

When the British Iron and Steel Research Association was formed, it was realized that the available laboratory accommodation was inadequate, and so premises were acquired at 140 Battersea Park Road, London, S.W.11. These were officially opened in October, 1947, by the late Lord Rayleigh, and now house the Chemistry and Physics Departments, the Plant Engineering Division, and the Corrosion Laboratories. Other branches of the Association working in London are the Ironmaking Division, whose Blast Furnace Research Laboratory is at the Imperial College of Science and Technology, South Kensington, and the Operational Research Section, based at the Association's headquarters, 11 Park Lane, W.1.

Since the headquarters of the learned societies and the more important scientific libraries are all within easy reach, London is better suited to the more fundamental side of the Association's work. Nevertheless, much of the work done in London is directly concerned with works problems, and most of the analysis of results obtained in works investigations is carried out there.

PHYSICS DEPARTMENT

The Physics Department was created to carry out research for all Divisions of the Association. Its functions are:

(1) To keep in touch with the advances of physical science with a view to possible application in the iron and steel industry
(2) To carry out research into the more fundamental physical problems connected with the work of the Association
(3) To carry out research and development in physics on behalf of the Divisions.

The department is divided into five sections:

(1) Fuel Technology
(2) Instruments
(3) Fluid Dynamics
(4) Steel Casting
(5) General Physics.

Fuel Technology

Work has been carried out on ingot heat conservation designed to reduce the fuel used in soaking pits to bring ingots to a uniform temperature before rolling in primary mills. In theory no fuel should be required to bring the ingot to the correct rolling temperature since the ingot when cast is much hotter than when it arrives at the mills, but in practice it is impossible to recover this excess heat economically. The problem of reducing unnecessary heat loss is being studied in three ways: by surveys of works practice in production, handling, and movement of ingots; by studying the rate of cooling of ingots, in an attempt to reduce stripping times to a minimum; and by studying the flow of ingots in works, to determine the optimum relationship between soaking-pit capacity and rate of ingot production.

The theory of mixing of free turbulent jets, in which category most flames used in the iron and steel industry fall, has been studied with a view to determining the rate of combustion and length of the flame. Equations have been derived relating the length of a free jet flame to its momentum flux, and thus to the flow conditions at the nozzle, and this experimental work has been extended to practical conditions.

As a result of fundamental work by the Fluid Dynamics Section, new open-hearth burners have been designed to make maximum use of available energy and reduce fuel consumption. These burners are of the steam-atomized and coke-oven-gas/oil types.

The section has also played an important part in the international investigation at Ymuiden of the radiation characteristics of liquid fuel and coke-oven-gas flames.

Other work undertaken by the section include investigations into the cleaning of blast-furnace gas, the temperature distribution in blast-furnace foundations, the emissivity of open-hearth refractories, and convective heat transfer from jets, and the development of instruments for temperature measurement, including suction pyrometers for gas temperature measurement, a surface pyrometer, total-radiation pyrometers, heat-flow meters, immersion pyrometers, multi-point switchboxes, and calibration furnaces.

Instruments

The functions of this section are fourfold :

(i) Design of industrial instruments
(ii) Design of research instruments
(iii) Advice on instrumentation problems and liaison between the steel and instrument industries
(iv) Fundamental work on measuring techniques.

Among the industrial instruments that have been evolved are a photo-electric dust monitor, a portable steel-plate thickness meter, an optical width meter for narrow strip, and a multi-channel recorder. The latter is capable of recording several rapidly changing variables on a single chart.

Research instruments include an automatic wire-drawing die profilograph, a wire temperature meter, and a magnetic permeameter. Of especial interest is a water-cooled periscope capable of scanning the whole interior of an O.H. furnace.

The general liaison services include the correlation of performance data, price, etc., of commercial equipments, and the preparation of summarized data and surveys of published literature.

Fundamental work in instrument techniques has been carried out in stereo-photography (applied to the study of the movement of a blast-furnace burden) and eddy current techniques, for the measurement of coating thicknesses, surface-flaw detection, etc.

Fluid Dynamics

Much of the work of the section has been concerned with the aerodynamics of O.H. furnaces, for which much use has been made of models. A study of oil jets has introduced a new concept of the function of burners as being primarily jet-thrust producers rather than atomizers. A burner nozzle designed on this principle has been introduced successfully into the industry.

Other investigations have included a study of turbulent diffusion in O.H. furnaces, measurement of gas velocity, and research into the aerodynamics of blast-furnaces.

Steel Casting

This section is primarily concerned with the development of the continuous casting process. Fundamental researches over a number of years led to the construction recently of the first B.I.S.R.A. industrial pilot plant. The first laboratory apparatus produced billets $1\frac{1}{2}$ in. dia. $\times$ 3 ft. 6 in., and later 3 in. dia. $\times$ 6 ft. Trouble was experienced at first from rupture of the billet skin within the mould, causing molten metal to flow out. This was overcome by mounting the water-cooled copper or brass mould on springs, which allowed it to move down with the billet when a rupture occurred, giving the skin time to thicken and strengthen. The problem of sticking has not yet been fully overcome, but the use of rapeseed oil as a lubricant has given good results, with little smoke produced.

The full-scale pilot plant was built at the Sheffield works of William Jessop and Sons, Ltd., and has been undergoing trials for six months. A new plant for further study of the process has recently been built at the B.I.S.R.A. Sheffield Laboratories. Alternative methods of producing solid steel continuously from the molten state are also being investigated by the London group. In one such process a steel strip is passed through a bath of molten steel, so that a coating of steel is deposited on its surface. This strip is then rolled down to its original thickness, giving a longer strip.

General Physics

This section has developed new techniques for studying phase changes in steels by X-ray methods. A direct X-ray method using a Geiger-Müller counter as detector has been evolved; the counter receives the reflection from a suitable set of crystallographic planes of atoms in the different crystalline structures of austenite and ferrite. This method is used to produce S-curves of known steels in a much shorter time than is required by the conventional methods. Other investigations include an examination of the possibilities of using X-ray methods for estimating the alloy contents of steels.

A research team was recently formed by arrangement with the Ministry of Supply to examine the behaviour of materials such as mild, carbon, and alloy steels under very high rates of strain, such as are produced by the impact of projectiles and under explosion conditions. Several new techniques have been evolved for this investigation.

CHEMISTRY DEPARTMENT

The Chemistry Department carries out both fundamental research and research into specific process and user problems. Close collaboration is maintained with other research associations and university departments. The work is handled by three sections:

(1) Physical Chemistry
(2) Refractories
(3) Corrosion.

Physical Chemistry

The work of this section is at present concerned with the physical chemistry of iron and steelmaking processes and of the properties of finished steel.

The application of physico-chemical methods to the elucidation of slag–metal and slag–gas reactions has been simplified by computing, from available data, the activities of ferrous oxide, manganous oxide, and phosphorus pentoxide in slags as a function of slag composition, and recently the sulphur reaction in iron and steelmaking processes has been examined on the basis of available gas–slag–metal equilibrium data. The equilibrium contents of oxygen, manganese,

phosphorus, and sulphur in steel under any slag have been determined and are being used to discover how closely the distributions of manganese, phosphorus, and sulphur between metal and slag approach equilibrium. Experiments have also been made to investigate the effects of silicon, manganese, and aluminium on sulphur transfer.

Work is also in progress on the thermodynamics of carbon dissolved in iron alloys, the heat of formation and heat contents of slag compounds, and the solubility of nitrogen and sulphur in iron and iron alloys.

Refractories

Attempts are being made, by improving refractories and alleviating the conditions to which they are exposed, to reduce costs and improve outputs.

In co-operation with the British Ceramic Research Association, the section is seeking the best sources of raw materials and the best gradings, moulding processes, and drying and firing schedules. The effect of undesirable constituents is being studied with a view to the removal or reduction of the most harmful.

Investigations are also in progress of the relative merits of different refractories in service, with special emphasis on the open-hearth roof. The factors affecting roof refractories, such as position, temperature, pressure, and atmosphere have been studied.

Other researches by the section are concerned with the contamination of bricks by chemical action, the insulation of water-cooled parts, and the improvement of immersion pyrometer sheaths.

Corrosion

The work of the Corrosion Section covers most aspects of the corrosion and protection of heavy structural iron and steel, and may be divided into five categories:

(i) Corrosion by air
(ii) Corrosion by water
(iii) Corrosion by soil
(iv) Protective coatings
(v) Methods of testing.

To study the corrosive effects of different atmospheres and environments, specimens have been exposed for periods of up to 15 years at a number of stations throughout Britain and the world. A detailed study of the effect of composition on corrosion resistance has also been carried out. The corrosion caused by industrial sulphur-bearing atmospheres has been studied in conjunction with the Fuel Research Station.

The corrosive effect of water has been studied with specific reference to such factors as welding and the use of inhibitors in fresh water. In both these tests and those on specimens buried in different types of soil, it has been found that alloying additions have much less effect in increasing resistance to corrosion than in atmospheric corrosion.

The researches into protective coatings have demonstrated the importance of correct surface preparation of the steel to receive the coating. Pickling or grit-blasting before painting are essential for steels to be exposed to the atmosphere. Close collaboration is maintained with the paint industry in the formulation of priming paints. The use of metallic coatings is also under investigation.

A Corrosion Advice Bureau has recently been organized, to advise on corrosion problems. Its services are free to members of the Association, and enquiries from non-members are accepted on a fee-paying basis.

PLANT ENGINEERING DIVISION

The Plant Engineering Division is responsible for investigating engineering aspects of the design and maintenance of iron and steel works plant and the handling and transport of materials and products. The Division has four sections:

(1) Fuel (under the direction of the Physics Department)
(2) Electrical Engineering
(3) Mechanical Engineering
(4) Civil Engineering.

These are housed at Battersea, where there are three light electrical laboratories, a mechanical engineering laboratory, and a heavy plant laboratory. Close liaison has been established with steelworks so that the results of the fundamental researches in the laboratory and the extensive investigations in iron and steelworks may be applied in practice.

Electrical Engineering

The section is primarily concerned with heavier electrical problems, although light current engineering is not neglected. A motor drives group is seeking to improve the matching of intermittently loaded motors to their drives and substantial progress has been made.

Pre-set and fully automatic closed-loop programme controls are being investigated by the automatic control group. The application of a pre-set control to the screwdown on a continuous hot strip mill to improve uniformity of gauge has proved highly successful, and experiments are now being made to apply position control to a reversing mill screwdown to reduce the supervision required. Position control is also being extended to the continuous casting process.

Other investigations include an ergonomic study of manual control in steelworks, designed to fit the controls to the operator, the application of oscillography and punched-tape techniques to works trials for measuring and recording, and the improvement of works communications, with especial reference to the use of V.H.F. radio.

Mechanical Engineering

The activities of the section cover the study of mechanical handling problems, investigations involving stress measurements, correlation of data on wear and tear of plant, and the evaluation of new types of equipment.

A comprehensive investigation covering many aspects of the handling and transport of imported iron ore was recently completed; this included a detailed study of the requirements of ore ships, and investigations into the time required for discharging at ports

and the methods of rail transport from port to ironworks. This led to a detailed examination of the relative merits of four- and two-axle wagons, which showed the latter to be preferable for carrying all but the heaviest ores, and also to a study of crane grab design, both in the laboratory and in full-scale trials at the docks.

The application of gas turbines for blast-furnace blowing is also under consideration. Investigations into sinter-plant operation have covered the control of feeder tables and the development of a simple flow meter and a dust trap for use on sinter plant windlegs. Work on roller tables has included measurements of the friction of slabs on the rollers, an investigation into the anchorage of the bearings, and the development of a photoelectric torque meter. Hydraulic systems are being developed for automatic gauge control on strip mills and for the feeding mechanism of a continuous casting unit.

Civil Engineering

The work of this section has included a major investigation of the layout of integrated iron and steel plants in the U.K., and a comparison of these with continental and U.S. layouts.

A survey of the design and layout of melting shops included attention to the elimination of structural distortion in O.H. furnaces and the improvement of electric overhead travelling crane design in relation to the structures which carry them. Detailed theoretical consideration is being given to crane gantry girders and their reactions to the heavy loads imposed on them.

The stresses in overhead cranes used in steelworks are being measured under working conditions and the results of the trials are being applied to the improvement of specifications and the saving of steel in the crane structure.

IRONMAKING DIVISION

The work of the Ironmaking Division is divided between the laboratories at Imperial College in London and those at Normanby, near Middlesbrough. The Normanby laboratories are engaged in developing and applying techniques to blast-furnaces, to increasing the understanding of the complex processes within them, and in improving methods of agglomerating fine ores. The fundamental work for these researches is largely carried out at the London laboratory, where, for example, an attempt is being made to establish the optimum conditions for the reduction of various lump ores. Possible means of desulphurizing iron outside the blast-furnace have been investigated in the laboratory, and subsequently in large-scale trials. The Imperial College Laboratory has made much use of X-ray powder-diffraction photography and microradiography for such problems as primary slag formation and the influence of coke, lime, size grading, etc., on the mineralogical composition of sinters.

Researches into the nature of the agglomeration processes of sintering and pelletizing have been carried out at South Kensington, where the correct conditions for firing and rolling have been established in the laboratory, and then applied in pilot plant at Normanby. Other methods of agglomeration, such as briquetting and the use of the rotary kiln, have also been examined.

A great deal of work has also been done by the Division on the statistical analysis of blast-furnace data. The multiplicity of factors affecting blast-furnace output and fuel consumption, such as the proportions, analysis, and physical properties of the raw materials, including fuel, the dimensions and structure of the furnace, and details of the operating technique, have been recorded and analysed, so as to produce coefficients showing the affect of one factor on another. This ' multivariate regression analysis ' gives a reliable assessment of what performance a furnace should attain under given circumstances, and should be of great value in diagnosing furnace defects, arranging relining programmes, and deciding future plant development.

OPERATIONAL RESEARCH

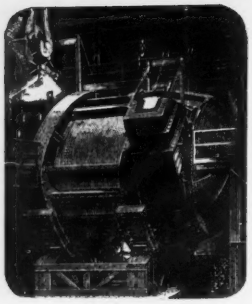
The responsibility of the Operational Research Section is primarily to investigate the organization of operations in the industry. It is concerned with the employment of resources, and relevant scientific techniques are applied to produce practical adjustments that would give higher efficiency.

One of the roles of the section is to advise and assist the divisions in the statistical design of experiments and the choice and analysis of operational data. Much use has been made recently of the electronic digital computer at Manchester University, especially for regression analysis of blast-furnace data. Another recent application of this machine was to the analysis of charging schedules for soaking pits, in connection with a study of ingot heat conservation.

A study has also been made of accident prevention in the iron and steel industry. It is hoped to go beyond the traditional means of avoiding accidents—that of guarding dangerous plant and machinery—which has been taken to its logical conclusion in most works, and to investigate the changes in the relationship of an individual to the community in which he works, which seem to be a source of " lost-time " injuries. Investigations to date suggest that a reduction in labour turnover, which reduces the number of very short-service employees, and an increase in the speed of learning to avoid injuries would both reduce accident rates.

The section has also been associated in a number of studies of traffic operating problems, such as the axle loadings on ore wagons and the relative operating characteristics of steam and diesel locomotives. Certain problems of works operations have also been studied, such as the avoidance of delay to O.H. furnaces charging scrap and the best transfer bloom size to give maximum output on combined cogging and billet mills.

A small advisory team has been established to undertake studies of this nature whose relevance is confined to a particular works and not the industry as a whole. Its services are available on request from individual companies.



AFFILIATED LOCAL SOCIETIES

Cleveland Institution of Engineers

The Design and Construction of Lackenby Steelworks

By A. P. Clark and S. Cornforth

SYNOPSIS

This paper describes the Lackenby Steelworks, which was designed for an output of 625,000 tons of ingots per annum, from five 360-ton open-hearth tilting furnaces, and two 600-ton active mixers, working 50–80% hot metal and producing mainly structural steels. The planning and development of the site, together with transport and materials-handling facilities and factors affecting the type and design of furnace, are discussed. Overhead revolving chargers are used in conjunction with a high-level stockbay and all molten metal is handled in the casting bay. Unusual features are the use of travelling ladle-teeming carriages, and the mechanical handling of lime, limestone, and dolomite. 1126

PART I—LAYOUT, GENERAL DESIGN, AND CONSTRUCTION

LAYOUT OF WORKS

IN 1946 DORMAN LONG AND CO., LTD., purchased the long narrow strip of land now known as the Lackenby site. In 1949 construction work began on the steelplant, and towards the end of 1953, the first steel was tapped. The general layout of the plant is shown in Fig. 1.

The Lackenby site is about 2½ miles long, and varies in width between 600 and 1100 yd. Its area is rather more than 1 sq. mile and its level varies by about 25 ft. between the highest and the lowest points.

Ultimately, this land is expected to be fully occupied by steel-furnace and rolling-mill plant, and therefore the first point to consider, in developing the site as a whole, was railway access between the works' system and the marshalling yards of British Railways. Since the mineral lines of British Railways lay on the N.W. side of the passenger lines, it was decided, in order to give direct access to the works without shunting across the passenger lines, to build a flyover bridge across the main lines at the western end of the site. The length of the site alongside the main line, from the flyover bridge to the corridor giving access to Wilton Works, a distance of about 1½ miles, was then laid out into four sets of exchange sidings. Each of these consisted of ten standage tracks, long enough to take trains of 50 wagons, so that complete trains could be brought from the marshalling yard on the west side of Middlesbrough and hauled straight into the Lackenby sidings. When the works has expanded sufficiently to require all these sidings there will be room for 2000 wagons. The importance of having ample sidings capacity may be realized when it is considered that eventually the Lackenby Works may have to handle up to four million tons of incoming and outgoing materials each year, carried in possibly over half a million wagons. At present, only one set of sidings has been laid, for the use of the steelplant.

The next step in developing the site was to decide how to lay out the various units of rolling-mill and steel-furnace plant which might ultimately be placed there. Naturally it was intended to use the land to the best advantage, at the same time ensuring an efficient layout of plant and railway systems. Modern steelworks plant tends to be of considerable length, far too great to be placed across a site averaging only

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Mr. Clark and Mr. Cornforth are with Dorman Long (Steel) Ltd., Middlesbrough.

800 yd. wide. On the other hand, it would be uneconomical in ground space, besides giving a bad railway layout, to place the plants lengthwise. Accordingly, it was decided that the various items of plant would be placed diagonally. This arrangement not only gave sufficient length for all the items of plant likely to be placed on the site, but also made for better railway curves at both ends.

These were only the preliminary steps which had to be taken in the general layout of the site. The first piece of working plant that it was intended to build was the present melting shop. This had to be designed to produce 10,000 tons of ingots per week, a figure later increased by adding another furnace, and the first decision which had to be made was on the size and type of furnace. Dorman Long and Co., Ltd., have had considerable experience in the operation of open-hearth furnaces of widely varying size, and this experience led them to the conclusion that, for structural steels, with the quality of blast-furnace metal and the proportion of scrap which could be expected in the Cleveland district, large tilting furnaces would prove to be more economical in operation than any other type.

It was decided, therefore, to build four furnaces, each large enough to give an average output (allowing for repair stoppages) of 2500 tons per week. For the blast-furnace metal there would be two fully active mixers, each of 600 tons actual capacity. The design and construction of these is dealt with later in the paper.

The size and type of furnace having been decided, no further progress could be made on the layout of the works until the method of charging the furnaces had been decided. The charging of steel furnaces was a few years ago the subject of a vigorous controversy in the steel industry, between those who advocated the use of fixed chargers with a railway immediately in front of the furnaces, and those who favoured the revolving charger, with a pan bench at the back of the stage. It was in this atmosphere that many schemes for the Lackenby plant were considered. Finally, however, it was decided to adopt a system of charging which had already proved successful with large tilting furnaces in one of the Company's older plants. With this system, the charge materials are raised, still in the wagons in which they arrive at the works, to a stockbay lying immediately behind and at the same level as the stage. Along one side of this bay is the bench on which the charging boxes stand to be filled by the overhead stockbay cranes and from which they are picked up by an overhead revolving charger. This charging method has the advantages that raising railway wagons to stage level is much more efficient than raising filled charging boxes, and that the whole of a furnace charge is available immediately behind the box bench. To reach the level of the stockbay, a long inclined ramp was required, flat enough to allow a works locomotive to push up the train of about ten wagons. The length of this ramp at Lackenby, allowing for the vertical curves and the fanning out of two ramp tracks into four stockbay tracks, is almost 1000 ft. The upper end of this ramp, and the railways leading into the stockbay, are shown in Fig. 11.

To keep all the incoming materials moving in one direction and clear of outgoing ingots and slag, this ramp has been placed at the south end of the works, remote from the exchange sidings, and the sorting and standage sidings are on the direct route between them. The main running roads are on the extreme east side to keep all running traffic clear of shunting. There are two grids of sidings, with a total capacity of 700 wagons—the main grid, alongside the ramp, for scrap and ore, and a smaller one for lime, limestone, dolomite, and other furnace charge materials. Wagons are pushed into the north end of the main grid and drawn from the south end, to be pushed straight up the ramp into the stockbay. The non-metallic and charge materials in the smaller grid are also drawn from its south end, to be dealt with in the raw-materials handling plant.

Outgoing ingots begin their journey in the stripper building (Fig. 8) at the south end of the plant alongside the ramp. Here hot ingots for the Company's Cleveland and Redcar Works can be loaded into special cars, eight to a car, and hauled, 150 tons at a time, under the ramp via the running roads to the inter-works link line. Ingots for the Company's other works must be kept until they are cold, and are then loaded into railway wagons. For slag there is under the stage a separate railtrack to each furnace, dividing into two spurs, one under each slag notch. These join a a common track on the east side of the shop, and slag ladles have only a short haul to a low slag bank lying between the melting-shop ancillary buildings and the main running roads.

The melting shop is the centre of the works, and around it are grouped the various smaller buildings containing ancillary plant. On the east (or chimney) side, in a long line alongside a road, are the skull-breaker gantry, the raw-materials handling building, the hydraulic and oil pump houses, and the oil tanks. Due south of the main shop is the stripper bay, about 200 yd. distant. On the west or casting-bay side is the main works road. Opposite the south-west corner of the main shop and connected to it by a footbridge at stage level is the main office block (Figs. 6 and 7). Immediately north of this is the building which houses the main electric substation, the furnace circulating pumps, and a 5000-kW. turbo-alternator using waste-heat steam. Also on this side of the main road are the canteen and the group of buildings forming the maintenance shops.

MELTING-SHOP BUILDING

The melting-shop building is 1083 ft. 4 in. long × 232 ft. wide, but space has been left at the north end to allow it to be extended by about 400 ft. to hold three more units. It is divided into three parallel crane bays, of 75 ft. span for the ladle cranes, 65 ft. for the chargers, and 65 ft. for the stockbay cranes. The longitudinal stanchion spacing over the furnaces is 125 ft. The furnaces and mixers have been arranged in pairs, and between the units of each pair is a short girder span, one-third of a full span, to give extra space in the shop for bins of ferro-alloys, for the fettling machines, and for two service lifts operating between ground and stage level. There is a similar short span at each end of the building. The furnace

charging stage is 22 ft. 6 in. above ground and the stockbay 20 ft. The stage is of concrete with steel filler beams, whilst the stockbay floor is ballast laid on steel troughing. Below the two stages is a wide expanse of floor, broken only by the regenerators, the slag roads, and groups of reversing dampers. A section through the melting shop is shown in Fig. 2.

The building generally follows traditional lines, but has some points of general interest. The stanchions are all of welded construction, with girder battens in place of diagonal bracing. This construction is not only more compact, but also allows openings through the stanchions for walkways and for pipe and cable runs. The system of girders over the furnaces is unusual. The casting-crane girder had to be high enough to allow the furnace to tilt and deep enough to carry the ladle crane without undue deflection. The crane rail was therefore made 63 ft. above the ground and 40 ft. 6 in. above the stage. This height was far too great to give a sound design of charger, and so the charger girder was supported on cantilevers from an auxiliary girder attached to the casting-crane girder by links. The two girders can deflect independently without twisting, and the charger rail is 11 ft. below the casting-crane rail.

As all the cranes are production machines, crane rails have received special attention. Pressures have been limited to 800 lb. per inch of width per inch of diameter for the ladle cranes, and to under 600 lb. for the chargers and stockbay cranes. The rails for the ladle cranes and chargers weigh 375 lb. per yard.

Safe and easy access has been provided, by gangways and stairs, to every point in the building where men must go, from floor to roof. The lights can be cleaned from gangways, and the roof glazing is accessible, outside from the protected gutters and inside from permanent trolleys, one under each stretch of glass.

Running across the casting bay and charger bay, at about eave level, are three 7½-ton crane-repair trolleys. These are remotely controlled from three platforms above the gantry girders.

STOCKBAY

In the elevated stockbay is the charging-box bench, a wide trimming platform, and four railtracks. The level of the rails has been fixed to bring the top of an average wagon about level with the top of a box standing on the bench. The two tracks nearest to the bench are for scrap and ore, the third is a running road, and the outer track is for lime and limestone. The charging-box benches occupy the full length of 125 ft. opposite each furnace, with 33 boxes on each bench. Overhead are four high-speed 20-ton magnet cranes. On these the magnet is permanently slung from three separate hoist ropes, spread like an inverted pyramid from two barrels. This method of suspension was designed to limit the swing of the magnet, and so to reduce the damage suffered by wagons when unloading scrap. Lime and limestone, in charging boxes, are kept on pallets, each holding four boxes. These can be transferred from the flat wagons on which they are kept to the bench by a lifting beam which can be clipped to the magnet on the overhead crane. This beam carries four hooks, and the crane driver can sling and unload a pallet without assistance.

CHARGER BAY

In the charger bay are four overhead revolving charging machines. The choice of the most suitable type of charger was regarded as a matter of some importance. A ground charger leaves the gantry free for a hot-metal transfer crane, but can interfere with other work on the stage, particularly furnace repairs. With these very large furnaces, it was thought to be of paramount importance to cut the furnace-rebuild time down to a minimum; this time could be reduced if the stage in front of the furnace were kept clear for the bricklayers and their materials and if space could be found for a railway track. The overhead charger was therefore chosen and hot-metal transfer was moved into the casting bay. The charging boxes are of 40 cu. ft. capacity, nearly twice the size of the boxes on the older plants. They will hold about 1⅓ tons of limestone, about 1 ton of scrap (though this varies widely), and nearly 3 tons of ore. The chargers are of 6 tons capacity, and the speeds of the various motions were chosen to give a continuous charging rate of one box per minute. This is very much slower than the rate for a modern fixed charger, but with the very long box bench and the four stockbay cranes, supplies of filled boxes are continuously available. The length of the charger carriage was kept down so that, combined with the long bench, two chargers could if necessary work at one furnace. Each machine has a 10-ton crab on the same bridge girders. This crab covers the furnace axis, so that chills and burners can be handled.

Between each pair of furnaces is a hydraulically operated service lift, of 15 tons capacity, with a platform 12 ft. × 8 ft., to lift from ground to stage level. These two lifts handle all the furnace alloy materials and dolomite, all of which are brought to the lift by fork-lift trucks from the raw-materials plant. The bins of ferro-alloy are stocked round the lifts on the stage. The lifts can also hoist furnace-repair materials, such as fireclay and pallets of bricks, brought to them by the fork-lift trucks, and can take doors down to the ground for rebricking.

A feature of this charging stage that is probably unusual is that it contains no stage laboratory. The samples are taken to a point between the two mixers, where they are drilled. The drillings are sent by pneumatic tube to the stage laboratory in the main office block, and the analysis is returned to the same point.

CASTING BAY

In the casting bay (Fig. 3) there are three ladle cranes of 160 tons capacity, with a 30-ton auxiliary trolley. The ladles are of 120 tons capacity. They are welded, except for the trunnions, which are riveted. Welding was adopted because it allows horizontal stiffening rings to be used in place of the bands on riveted ladles, and far greater stiffness of the ladle against distortion is obtained. The same size of ladle is used for transferring metal from the mixers.

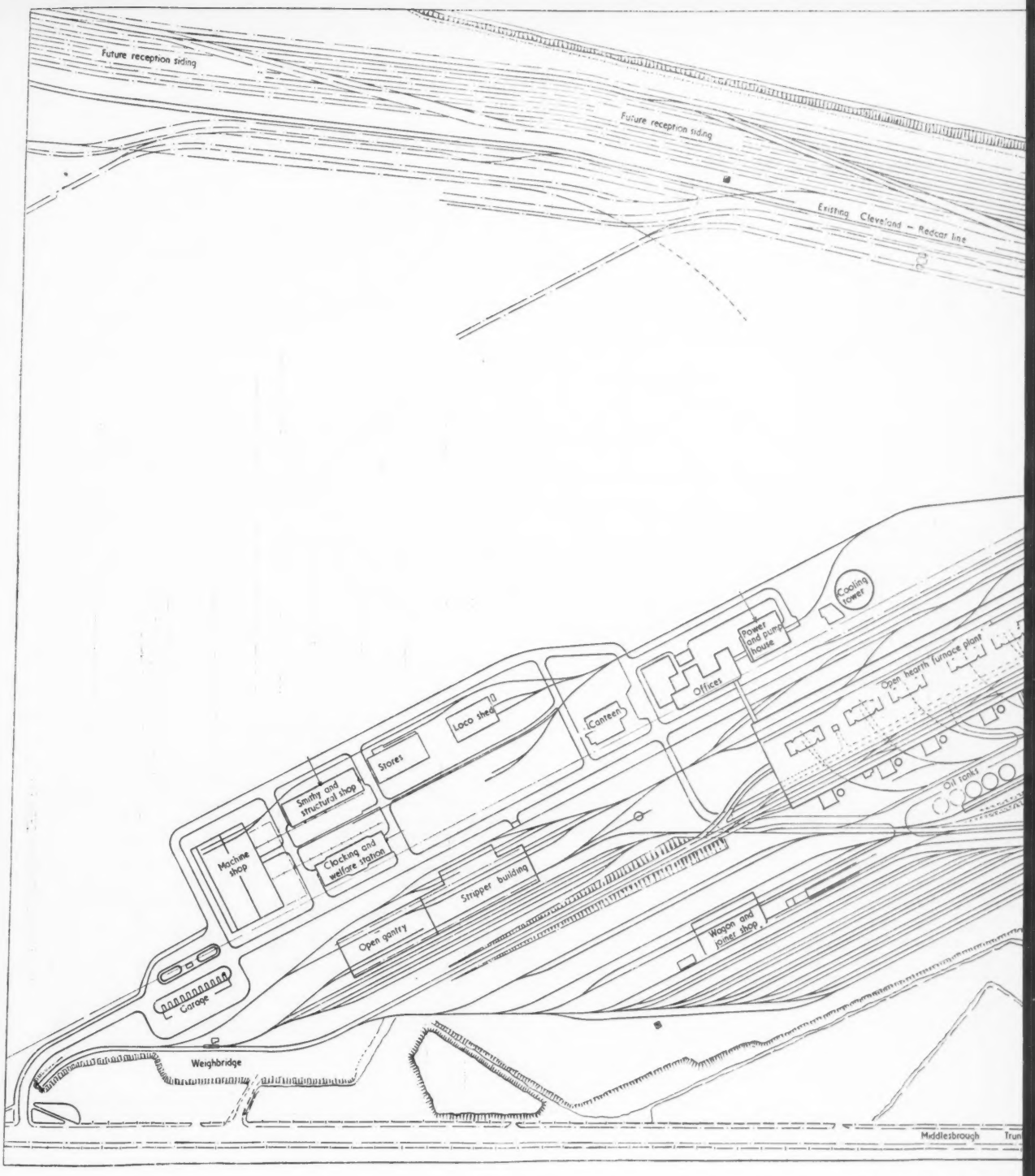
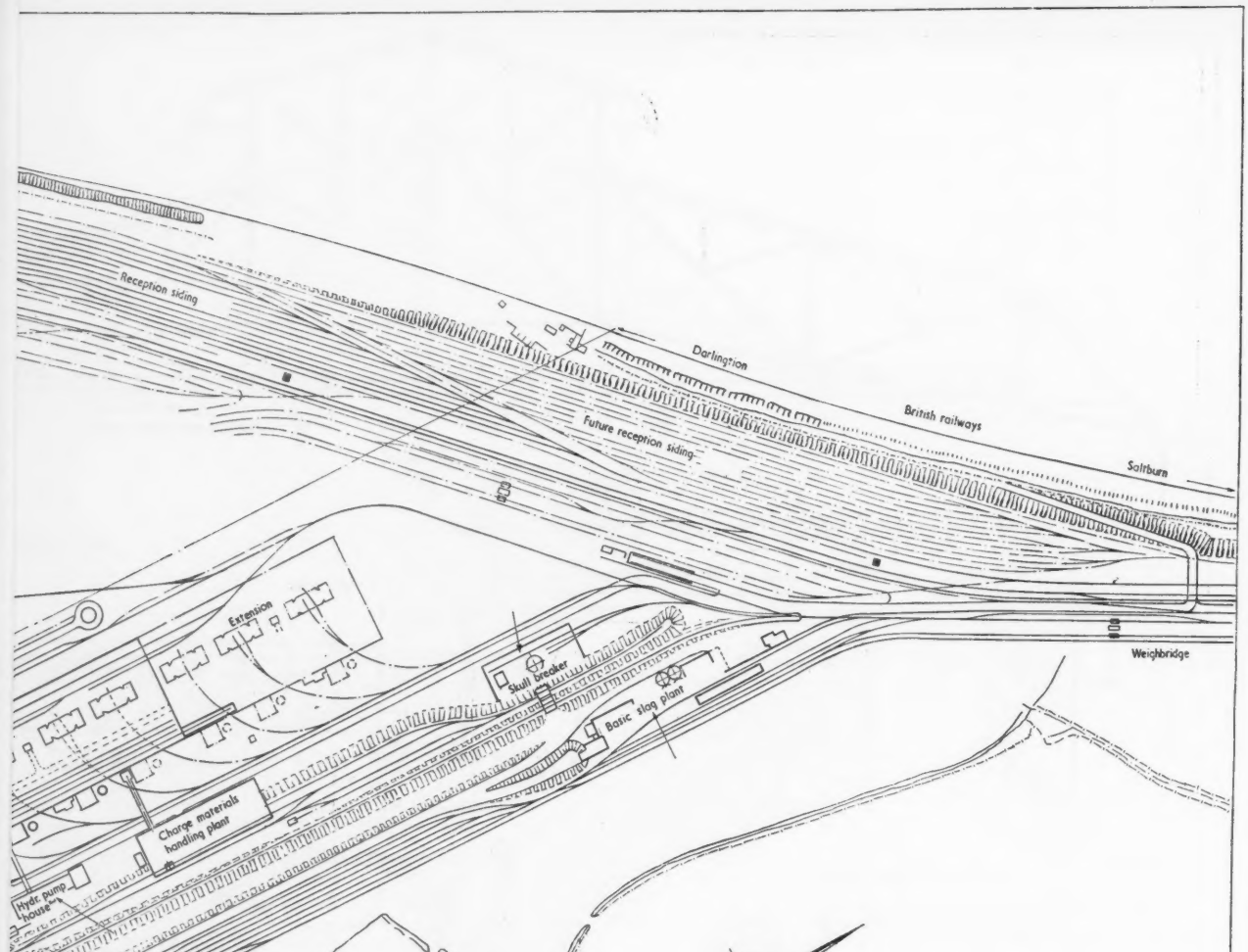


Fig. 1—General layo



ıt of Lackenby Works

[*Clark and Cornforth*
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In this bay, in addition to the ladle cranes, are three travelling ladle carriages of unusual design. These have one rail 10 ft. above the teeming platform and the other down on the casting-bay floor, outside the teeming road. These machines can carry a ladle, placed on the carriage by the crane, the full length of the shop and place it over any mould for teeming.

A machine of this kind was needed because the layout of the shop and the size of the furnaces both introduced their own difficulty in teeming. In the first place, the handling of mixer metal in this bay meant that ladle cranes must be able to travel with more freedom than if they had not this extra duty to do. In the second place, as the furnace capacity rises so the teeming space becomes more congested, since the length of a furnace is not proportional to its size. For instance, a 150-ton furnace occupies about 100–110 ft. of shop length, whereas the Lackenby furnace of 360 tons only takes 125 ft. In fact, when pouring 4-ton ingots, the contents of a single ladle requires over 100 ft. of shop length. The best solution of this problem appeared to be not to add more cranes but to allow the crane to get rid of the ladle as soon as possible. The fixed ladle stand did not seem to be a complete answer, as the crane would still have to travel to it and might be prevented from doing so by another crane. Also, a fixed stand requires shop length equal to twice the length of the rake of ingot cars. The teeming carriage adopted can be described as a travelling ladle stand, available anywhere in the shop.

These machines have electrically operated long-travel and cross-traverse motions, pendant-controlled from the teeming platform. The main semi-portal frame and the traversing trolley are both open-sided, so that the ladle does not have to be lifted any higher than necessary. The ladle sits, on extensions to its bottom stiffening ring, on a kind of cradle hung from the trolley, made of two **L**-shaped girders resting on two **U**-shaped girders, a deep one at the shop side, and a shallow one on the teemer's side. For different mould heights, packers of varying thickness are placed on the **L** girders.

FURNACE RAW-MATERIALS HANDLING PLANT

The building where lime, limestone, dolomite, and other materials required in the furnace charge are handled and prepared is on the east side of the main shop. The first three of these, all dusty, have always proved difficult to deal with satisfactorily. The Company had, however, already installed mechanical plant, with dust extractors, for crushing and loading dolomite, and for Lackenby it was decided to go a step further and tackle the loading of lime and limestone by mechanical means straight from the wagon into charging boxes. A number of schemes were tried, all centred round filling the boxes within the raw-materials handling building. Finally, a member of the Company's staff suggested that the box filling should be done within the stockbay, where the boxes were wanted. This suggestion proved to be the key to the problem, and within a short time the layout as it now stands was roughed out.

The building is 270 ft. long × 70 ft. wide, with a wagon leanto along one side in which the train of wagons can have the sheets removed. The wagons, which have previously been pushed up a ramp to an elevated track beyond the building, are let down one by one by gravity on to a tippler of dustproof design. As the wagon platform rises it meets a curved hood, whilst end shields come down to meet the platform, completely enclosing the wagon. As the wagon tips its load, the displaced air is forced into a large chamber over the hopper. A valve on top of the chamber lets clean air out as the dust cloud rises and closes on the return of the tippler, to create a partial vacuum and so to prevent dust escaping past the wagon. From the tippler hopper twin skips raise the tipped material and discharge into one of the three storage bunkers placed in line ahead, one for each of the three materials. From these bunkers lime and limestone are carried by two further automatic skip hoists, up and across to two high-level service bunkers alongside the stockbay. The skip-hoist gantry is shown in Fig. 12. The service bunkers are partly seen behind the nearest chimney. At the outlet of each of these a retracting belt feeder fills each charging box from end to end with a practically constant quantity. The boxes stand in sets of four on the pallets on which they are lifted across to the charging-box bench, and each pallet stands on a flat wagon. The wagons are hauled past the belt feeder by a wagon haulage gear fitted between the rails, stopping to allow each box to be filled. The service bunkers hold 50 tons each, and the stockbay railroad can accommodate 40 wagons (i.e. 160 boxes), so that when all the boxes are full and the service bunkers replenished the available stock of the two materials actually in the shop may be 300 tons. It was intended that the whole of the lime and limestone required for three shifts could be handled on the day shift only. Dolomite is fed from its storage bunker into a swing hammer mill; from here a bucket elevator delivers it into a second bunker in the middle of the shop, from which portable bins can be filled by a belt feeder. These bins are simply the top hoppers from the dolomite fettling machines, enlarged to hold about 4 tons of dolomite. All the skip hoists, elevators, and bunkers in this plant are in plated or sheeted enclosures, so that none of the moving parts can be seen. In addition to this enclosure for keeping dust under control, at all points where dust clouds are caused extraction hoods, connected to a central filter plant, are fitted. About 20 tons of dust is collected each week.

The remaining furnace materials are brought into the building on a high-level railtrack and stored in open bunkers below (Fig. 11). In front of the bunkers are the three pan mills for mortar, fireclay, and tarred dolomite and the crusher for ferromanganese. All these materials are carried to the two service lifts by fork-lift trucks of 12,000 lb. capacity. These trucks carry the hoppers of dolomite, bins holding 3 tons of ferromanganese, skips of fireclay, or pallets loaded with bags of anthracite.

SERVICES

As Lackenby was a complete new works, all the usual services—electricity, gas, cooling water, pressure

water, steam, and compressed air—had to be provided. Steam is supplied from waste-heat boilers at each furnace and mixer, and what is not required for oil atomizing and other services is used in the 5000-kW. turbo-alternator. For furnace cooling water a common system on Tees Valley water serves both the furnaces and the turbo-alternator. Water from the cooling-tower sump is pumped through the condenser and flows direct into the furnace pumps, which send it round the furnaces and back to the cooling tower in a closed system under pressure. The supply and return mains are connected to both ends of the plant, with valves placed so that any section of main can be shut off in an emergency or for cleaning out.

All the motions on the furnaces—door lifting, vessel tilting, and port-block retracting—are operated by hydraulic power. The demand for water by steel furnaces can be very variable, ranging in a matter of seconds from zero to possibly 1000 gal./min. The three pumps, each of 300 gal./min., therefore work in conjunction with a 400-gal. air-loaded accumulator, and the controls start up successive pumps as required. Electric power at 11 kV. is brought from the B.E.A. Grid to the power station, with connections to Cleveland and Redcar works. Because of the area of the works, and in view of future developments, a primary network has been established within the works at this voltage, connected to four transformers at suitable points.

FOUNDATIONS AND ERECTION

Foundation work began on the Lackenby site within a few weeks of receiving instructions to proceed with the building of the plant. Trial boreholes had already shown that the ground was boulder clay, overlying a bed of shale between 16 and 30 ft. down. It was decided that all concrete would be founded on the clay and spread sufficiently to keep pressures down to 3 tons/sq. ft. These pressures would be increased where shale was found.

In planning the sequence of foundation and construction work, it was early realized that the major problem was the melting-shop building and furnaces. Within this building were concentrated three-quarters of the concrete, three-quarters of the structural steelwork, and, incidentally, about three-quarters of the cost. Because the large girders and stanchions were too bulky and heavy to carry from the Britannia Works, a fabricating shop had to be found on the site, and so the stripper building, equipped with two cranes, was the first building to go up. The largest and heaviest pieces were the ladle-crane gantry girders over the furnaces. These weighed 137 tons each and were made in four pieces and riveted up at erection.

The smaller buildings and items of plant were erected as soon as drawings could be issued and the equipment gathered together. No particular order was observed or found necessary, except that items of equipment with long delivery times had to be dealt with first. The main shop was a different proposition, and had to be planned beforehand. The shop was divided into three approximately equal sections and all construction gangs were started off at the south end. The excavation was first, and when this had moved on to the second section foundation work began on the first. As these two gangs moved on, they were followed by the building constructors, who in turn were followed by the builders of the furnace steelwork. A few problems cropped up from time to time. The brickwork of the flues, for instance, had to be done early, so that the erection derrick could pass over, and where the derrick track crossed the flue temporary girders on concrete piers had to be placed. For the large girders temporary trestles were required, and the floor of the regenerators had to be strengthened to carry them. The erection railways were moved along to suit the various erectors, and gradually each gang worked north until they finished at the north end of the plant.

There were, of course, many other items of plant to design and construct besides those dealt with already, such as the engineering workshops, the skull breaker, the basic slag plant, and the rolling stock.

One final point perhaps deserves mention—the general appearance of the sheeted buildings. A departure has been made with the Lackenby buildings from the idea that a steel-sheeted building can be no more than a shed, to keep out the weather. The eave line has been accentuated by sheeted gutter guards in place of the more usual handrailing. On the larger buildings the end section of roof has been made flat, to improve the general appearance. Pilasters of light structure, covered with corrugated sheets, have been placed at the corners of the buildings, and along the sides to break up the large flat areas.

Part II—FURNACES, MIXERS, AND FUEL-SUPPLY SYSTEMS

By S. Cornforth

DESIGN FACTORS

THE MAIN PURPOSE of the steelplant is the supply of ingots to a universal beam and heavy-section mill, and to other mills for which preparations are now being made along the west or Grangetown side of the present works. The steels to be made will be mainly plain carbon and low-alloy semi-killed structurals, and quality requirements are expected to fall within a narrow range. The future ironmaking and scrap supply position is expected to be such that the plant will work within 50–80% hot metal. For the basic open-hearth process, conditions such as these favour 'bulk steelmaking,' and there are economic advantages to be gained by the use of steel furnaces of the largest size that can be worked, served, and maintained satisfactorily.

Fig. 3—View of casting bay from casting-crane gantry. Wide platforms have been provided at all necessary levels.

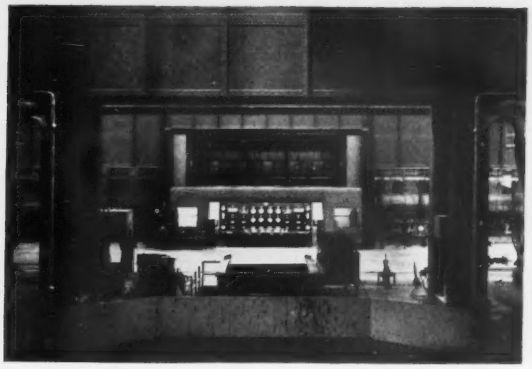

Fig. 4—Control station and furnacemen's cabins for two furnaces. In foreground top of stage lift and skips of ferromanganese; the lift is loaded at ground level by fork-lift truck

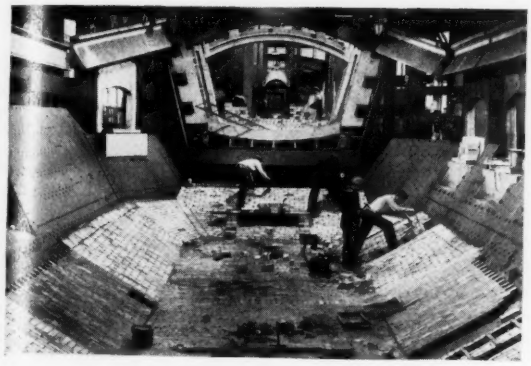

Fig. 5—Interior of 360-ton tilting furnace vessel structure, with water-cooled door frames, chills, and skewbacks. Bricklayers laying 4½-in. fire-brick lining of pan

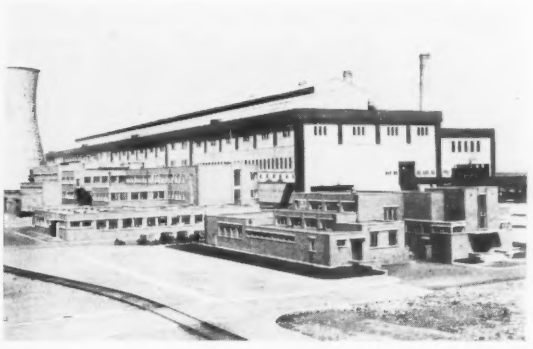

Fig. 6—View of melting shop from S.W. In the foreground is the works canteen and to the left is the main office block. Left of this can be seen the pumphouse and power-house, with the cooling tower behind

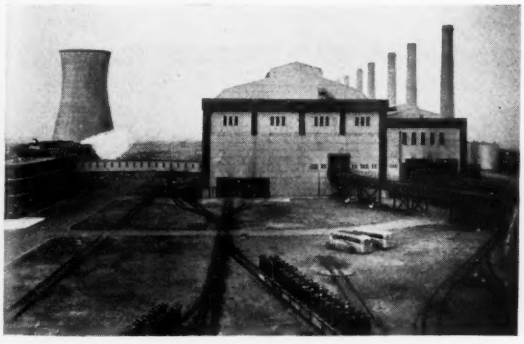

Fig. 7—South gable of melting shop from roof of stripper building. The passenger bridge connects the main office to the charging stage

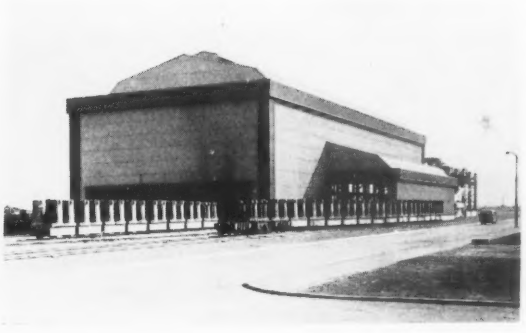

Fig. 8—Stripper building and main works road, with ingot stock gantry in background

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Fig. 9—360-ton furnace at maximum tilt, from charging stage

Fig. 10—Furnace raw-materials handling plant. Furnace alloys are stocked in open bunkers under the elevated rail track. The portable bins, shown on the left, are taken by fork-lift truck to the charging-stage lifts

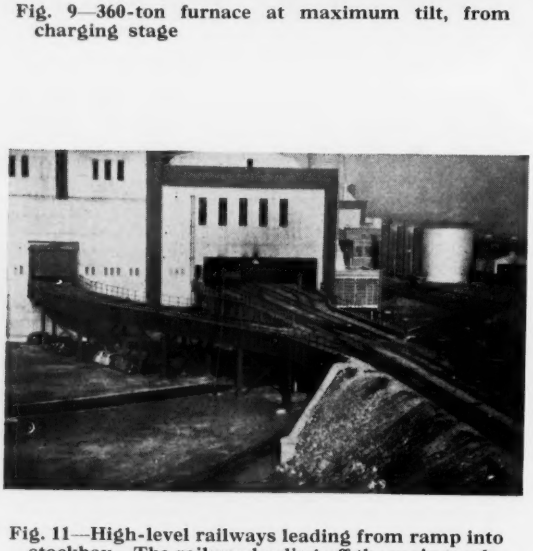

Fig. 11—High-level railways leading from ramp into stockbay. The railway leading off the main tracks is a repair road running in front of all the furnaces

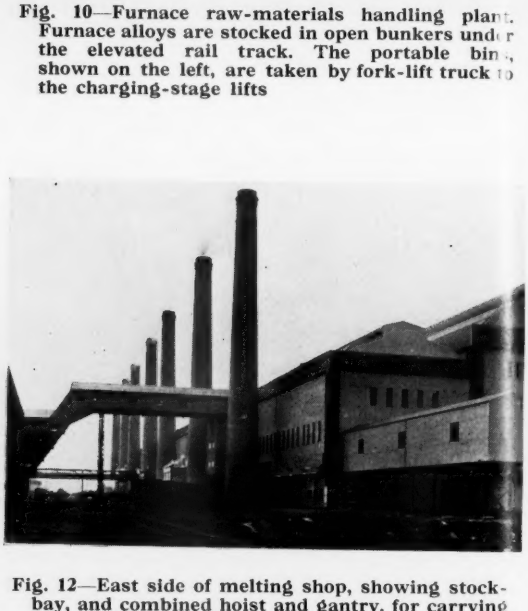

Fig. 12—East side of melting shop, showing stock-bay, and combined hoist and gantry, for carrying skips of lime and limestone from materials-handling plant to service bunkers at side of stock bay

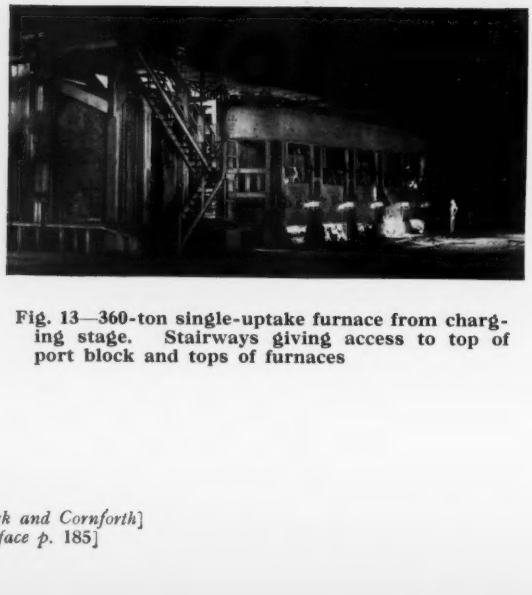

Fig. 13—360-ton single-uptake furnace from charging stage. Stairways giving access to top of port block and tops of furnaces

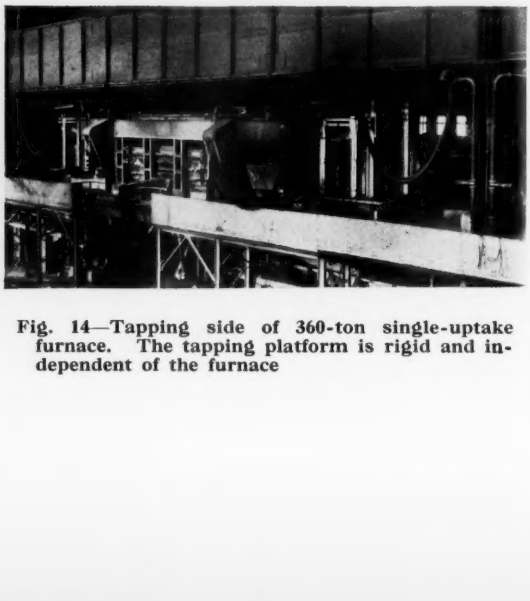

Fig. 14—Tapping side of 360-ton single-uptake furnace. The tapping platform is rigid and independent of the furnace

Fixed furnaces have a lower first cost than tilters, but they appear to reach an economic limit with a capacity of 200–225 tons, and they are not suitable for high hot-metal working, except when the metal is of really good quality. Large fixed furnaces would be very difficult to maintain in production when using dolomite as a hearth-lining material, if the metal quality were to deteriorate badly and silicon and sulphur to become a problem, as happened during the war as a result of using unsuitable materials at the blast-furnaces. Tilting furnaces, on the other hand, are able to subdivide the charge, can handle large slag bulks satisfactorily, and can drain the hearth rapidly for bottom repairs. The older tilting furnaces of Dorman Long and Co., Ltd., are severely handicapped both in heat input and speed of working owing to space restrictions. In spite of this, experience over a long period has been that large tilting furnaces have produced cheaper ingots than the fixed-furnace shops. This is based in general on the working of fairly high hot-metal charges.

For many years, O.H. furnace design within the Company has been limited to enlarging or modifying existing furnaces, or occasionally designing a new furnace to fit into an existing building. In all cases it has been a matter of making the best use of available space and accepting the design limitations thereby imposed.

When the opportunity came to design furnaces for Lackenby, this approach was inverted, and it became necessary to determine, as rapidly as possible, the space requirements of a furnace designed specifically for the Lackenby conditions, so that buildings and foundations could be designed and site work might begin.

The removal of the upper limit on dimensions made it necessary first to determine an optimum capacity for the furnace. It also became possible to think of design in terms of performance and thermal efficiency, and to consider the qualities that would be most desirable in an ideal furnace. These were defined as

High output
Low maintenance
Long campaign life
High thermal efficiency

On the older tilting furnaces, these ideals are almost entirely incompatible. High output in general would necessitate high heat input, and this would almost certainly cause high maintenance or a shorter campaign life, coupled with relatively low thermal efficiency.

There is one design factor which, if it could be achieved, would bring all these four ideals into line, and this has been the primary aim in the design of the Lackenby furnaces. The design should ensure that the maximum possible amount of heat is transferred from the flame and combustion products directly into the charge. From this it would follow that the outgoing gases would leave the vessel at the lowest practicable temperature and would be incapable of causing serious damage to blocks, downtakes, and slag pockets. The limit in this respect would be a temperature only sufficiently above that of the slag surface to ensure that heat transfer would continue right to the end of the bath. The short length of travel of heat from its source in the flame to its destination in the bath would reduce the opportunity for losses and should give a high thermal efficiency.

It would also follow that regenerators must be large and efficient to produce a high preheat temperature in the combustion air from the smaller amount of heat available in the waste gases.

FURNACES

The output decided upon for the new plant was 500,000 tons per annum from four furnaces. This has since been increased to 625,000 tons per annum by the addition of a fifth furnace. After allowing downtime for repairs, each furnace would thus be required to average 2780 tons per week throughout each campaign and, with an assumed capacity of 360 tons of ingots per charge, would have to average $7\frac{3}{4}$ charges per week, with a tap-to-tap time of about 22 hr.

After an extensive survey of steelmaking practice, the heat input for the Lackenby furnaces was fixed at an average rate of 860 therms/hr., with a peak input 50% greater.

The maximum depth of hearth was fixed at 48 in. as for the older furnaces, and the hearth dimensions adopted were 50 ft. × 18 ft. at foreplate level. This gave a length/breadth ratio of 2·78 and a net hearth area of 830 sq. ft. The width of 18 ft. presupposed the use of a dolomite-throwing machine for fettling the back bank and back wall.

With this hearth area, the average production rate required is approx. 45 lb./sq. ft. hr. The designed heat input is just over 1 therm/sq. ft. hr. and, relating heat input to steel output, gives 43·5 lb./therm or a little over 50 therms/ton. The final design of port ends for oil firing was based on an anticipated fuel consumption of 38–42 therms/ton. These figures have been deliberately fixed on the conservative side to cover difficult steelmaking conditions, coupled with provision for the use at some time of producer gas as fuel. The fuel at present in use is fuel oil, with in addition a small amount of coke-oven gas at the mixers, but the plant is designed to use any of the common steelmaking fuels.

For strength purposes the maximum charge weight was taken as 550 tons, to allow charges to be increased to 480–500 tons (i.e. four 120-ton ladles). The vessel steelwork is 62 ft. long over chills with a width of 31 ft. 4 in., and the total length over the vessel and two port ends is 99 ft. The area at the chills is 97 sq. ft., the downtakes are 81 sq. ft., and the slag pockets are 25 ft. long, 8 ft. 6 in. and 13 ft. 9 in. wide, and 13 ft. 9 in. and 15 ft. 9 in. high above paving level.

The regenerators are proportioned for producer-gas firing. For oil firing the two at each end are coupled together by pressure balancing openings through the centre wall above and below the checkers, and both are used for combustion air. The checkers have a height above bearers of 14 ft. 9 in. and a total volume of 11,700 cu. ft. at each end. Bearer flues under the checkers have a clear height of 5 ft. 9 in. The regenerators are 30 ft. long, 9 ft. 9 in. and 16 ft. 3 in. wide, and 28 ft. 6 in. and 31 ft. 1 in. high.

The flues are in the form of a large **Y**. Separate air and gas flues run from the regenerators to the junction point and unite into a single flue leading directly to the waste-heat boiler uptake, with a bypass flue to the stack branching off at 45°.

Owing to the method used for excavating for foundations, a space was left under the slag pockets. This has been turned to advantage by extending the ferro-concrete casing walls of the regenerators, and supporting the slag pockets from these by a series of 22 in. × 7 in. joists spaced at 2 ft. centres, surmounted by an 18 in. slab of Ciment Fondu refractory concrete, which forms the floor of the pockets. The chamber thus formed under the pockets is 30 ft. × 32 ft. with a height of 14 ft. 2 in. It is ventilated and provides access to the bearer flues under the checkers.

Bearer girders carrying the furnace supporting rollers are 22 ft. 6 in. long, 4 ft. 3 in. wide, and 42 in. deep. The two main foundation blocks are of reinforced concrete and each is designed for a load of 800 tons. The centre portion of each bearer girder is filled with reinforced concrete and forms a jacking platform from which one end of the furnace vessel, complete with lining, can if necessary be lifted by hydraulic jacks, to permit the removal of rollers and bearings for maintenance purposes. There are four rollers per rocker, and each pair is mounted in a cast-steel compensating frame, transmitting the load to a single pin in the heavy cast-steel bearing pedestal.

Each furnace has two rockers, with a radius of 15 ft. 6 in. The roller path is of 40-ton tensile steel in the form of a universal flat, 2 ft. 4 in. wide and 2 in. thick with rolled edges. The pan is supported on ten longitudinal girders arranged in three groups; the centre group comprises four girders, 42 in. deep with 12 in. × 1½ in. flanges, and each side group comprises three similar girders 36 in. deep. The total rolling load is about 1500 tons.

The rockers are spaced at 35 ft. centres to leave space for two slag-ladle tracks beneath the furnace. The slag ladles are of 235 cu. ft. or 17 tons capacity and they are spaced to bring them under the slag notches at the second and fourth furnace doors.

Buckstays are 18 in. × 6 in. straight solid slabs in pairs, tied across the top of the furnace by 12 in. × 2 in. flats. The buckstays transmit bursting forces from the roof and hearth to two horizontal girders; the upper forms a platform 3 ft. wide around the top of the furnace giving access to door-lifting pulleys and pipework, and the lower one is a girdle encircling the furnace at charging-stage level.

Port ends are retractable and have water-sealed uptakes. Each port-block structure has four heavy cast-steel wheels, supported on 375 lb./yd. rails, on track girders which can be raised by four 22 in. dia. hydraulic cylinders. By this means the whole port block and its supporting girders can be raised 18 in. to lift the dippers clear of the seal troughs. The block can then be retracted a distance of 11 ft. by hydraulic ratchet-type pull-back gear, mounted on each port-track girder. Two sections of stage can be removed from behind the block and replaced between port block and furnace end to form a working platform (Fig. 14).

The lifting type of retractable port block avoids the complication and space requirements of any type of seal-lifting gear, and permits an unrestricted uptake design.

Each furnace has two hydraulic tilting cylinders. These are 28 in. bore and have a barrel length of 20 ft. 3 in. Piston rods are 12 in. dia. and 28 ft. 7¾ in. long. The furnaces and mixers have a maximum tapping tilt of 35° (Fig. 9) and will tilt 15° to the stage side for slagging off.

The end frames of the furnace vessel steelwork are fabricated from 24 in. × 7½ in. joists, but the main vertical and horizontal members in contact with brickwork and subject to heat damage are 24 in. × 6 in. solid slabs. The horizontal slabs take the main hearth thrust and are welded to the verticals.

All doors have water-cooled tank-type door frames. Particular care has been taken to reduce to a minimum air infiltration at the doors. The doors are raised by hydraulic cylinders, and when fully lowered come to rest on steel wedge castings, which press them into close contact with the door frames. The doors overlap the sills by about 6 in. and, to avoid the gap which usually exists at this point, the water-cooled frames are made to surround the door openings completely and the doors make sliding contact with the frames on all sides, including the sill. Doors are of cast steel, cambered in both vertical and horizontal planes, and have a 4½ in. brick lining. The door castings are protected from direct furnace heat and have a long life. Wedge castings which retain the doors in place are hinged and a door can be carried away by the charging machine after unhooking the door chain and removing two locking pins. The charging side of a single-uptake furnace is shown in Fig. 13.

The plan area of the vessel top steelwork is made as small as possible to facilitate access to roof brickwork for hot repairs. For this reason small slabs rather than structural sections are used as transverse tie members, and gussets at the junction points of cross bracing are star-shaped to avoid as far as possible making any part of the roof brickwork inaccessible.

Roof skewbacks over all doors are hematite iron castings and are water-cooled. Tapping-side skewbacks are fabricated from part-rolled 18 in. × 6 in. steel joists taken off the mill after the first roughing stand.

In the building of the hearths (Fig. 5) 1½ in. of insulating concrete is laid on the shell plating to cover butt straps and rivet heads, followed by 4½ in. of firebrick and 18 in. of magnesite brick. The latter is laid as two 9-in. courses with bricks on end. The hearth lining is of dolomite 15 in. thick, 9 in. of which is rammed and the remainder burnt in. At the front side the magnesite of hearth and banks is carried up to a height of five courses above foreplate level, above which the front lining is of chrome-magnesite with silica door arches. The furnaces have five equal charging doors with openings 4 ft. high × 5 ft. wide tapering to 4 ft. at sill level. The tapered form was chosen to give a more satisfactory design of brickwork pillar between doors without restricting door openings.

The back walls are fully sloping except for a vertical portion 2 ft. high immediately under the roof. The magnesite brickwork of the back bank continues to the top of the slope and the vertical portion is con-

structed of 4 in. dia. magnesite tubes. Vessel and port end chills are of hematite iron with cooling pipes cast in, and are in four pieces, removable separately. The top chills have a quick-release device to facilitate chill changing. The main roof has a span of 24 ft. between walls and a length over chills of 62 ft., with a rise of 3 ft. 3 in., and a height at centre above foreplate of 9 ft.; it is 15 in. thick with 18 in. ribs.

Port blocks are built entirely of silica brick, with the exception of the nose of the doghouse, which is of chrome-magnesite. Furnaces *A* and *B* and Mixers 1 and 2 have normal twin-uptake port ends. Furnaces *C*, *D*, and *E* have single uptakes. Slag pockets and uptakes are built entirely of silica brick. The uptakes of both twin- and single-uptake furnaces have the same area, approx. 81 sq. ft. at each end. Single uptakes are elliptical in shape, 7 ft. long and 15 ft. wide. The mixers, in common with the furnaces, are designed below stage for producer-gas firing and the general construction is similar. The large and small slag pockets are respectively 11 ft. 6 in. and 7 ft. wide, 14 ft. 10 in. and 13 ft. high, and 24 ft. long. The regenerators have a checker volume of 7800 cu. ft. at each end. The large and small chambers are respectively 13 ft. and 8 ft. wide, 31 ft. 1 in. and 28 ft. 10 in. high, and 24 ft. long, and the checker depth is 15 ft. 6 in. above bearer arches.

The end wall of each slag pocket was built as a series of arches so that if it were later decided to use a mechanical loader in the pockets for removal of slag, the whole end wall could be removed if necessary and the opening closed by a single 18-in. stopper wall. This has now been done, and the slag is removed rapidly by an Eimco shovel which loads it directly into a Euclid truck in the casting bay.

MIXERS

The two mixers each have a designed metal capacity of 600 tons to 9 in. below foreplate level. The hearths are 51 ft. × 19 ft. 6 in. with a net area of 913 sq. ft. at foreplate level and a depth at centre of 7 ft. They are designed for active working with side and end banks at such an angle that they can be fully fettled when standing level, and without loss of capacity.

Each mixer is intended to serve three furnaces; it has a designed heat input of 570 therms/hr., and with a throughput of about 7000 tons per week should be able to melt 1600 tons of cold scrap per week if required.

The lining of the vessel is similar to that of the furnaces. Front and back linings are nearly vertical, the front being of silica with five doors. The centre and two end doors are standard with those on the furnaces, with a single slag notch at the centre door. The intermediate doors are larger to permit the charging of heavy scrap. They have openings 6 ft. wide tapering to 5 ft. with a height of 4 ft. The mixer body has cone-shaped ends below foreplate level and above this is tapered to form shoulders in which the end doors are positioned. The back lining is built of 4-in. dia. magnesite tubes. The shoulders are of chrome-magnesite and the two hot-metal doors are positioned in the shoulders on the tapping side. These doors are standard with the hot-metal doors on the steel furnaces. Blast-furnace iron is brought into the pit side in 75-ton Kling ladles, and charged into the mixers by the pit-side cranes, through a swivelling spout similar to that used on the furnaces for mixer metal. The mixer vessel steelwork is 63 ft. long over chills and 31 ft. 4 in. wide. The pan is 27 ft. 6 in. wide between buckstays and has a depth below foreplate of 10 ft. 2 in. The bottom radius is 11 ft. and the plating at each side slopes up at an angle of 48° to the horizontal. There are nine radial pan-supporting girders 42 in. deep with 12-in. flanges. The rockers are at 32 ft. centres and their general design is similar to the furnace rockers. Supporting rollers, bearings, and tilting cylinders are standard with those on the furnaces.

The mixer-vessel end openings are 12 ft. wide and have an area of 69 sq. ft. The port ends are similar to those of furnaces *A* and *B*, but smaller in size. The twin uptakes are each 4 ft. 6 in. × 5 ft., giving a total area of 45 sq. ft. The outer curved end wall of the port end on the single-uptake furnaces receives the direct impingement of the waste gases leaving the hearth. It is built of silica brick in the form of an arch with axis vertical. It is 42 in. thick and after a campaign of 19 weeks this has been reduced locally to a thickness of 4½ in. It is repaired by building inside it and making it up again to its original thickness. The coke-oven-gas burners are 12½ in. dia. × 16 ft. 10 in. long. A 6-ft. length at the nose is water-cooled and has an 8-in. dia. coke-oven-gas tube with a 5-in. dia. nozzle. A 1½-in. dia. oil tube with a ⅞-in. nozzle is positioned inside the coke-oven-gas burner and has a Krause No. 3 atomizer at the rear.

FUEL-SUPPLY SYSTEMS

A 24-in. steel coke-oven-gas main is supported under the stage for the length of the plant and there is a 12-in. connection to each furnace and mixer. Pressure in the main is controlled by an Askania regulator. The supply to each mixer is regulated manually by butterfly valves remotely controlled from the respective control desks. Reversal is by hydraulically operated sluice valves mounted on top of each port end, as closely as possible to the burner, and manually controlled from two ½-in. double-ported valves at the control desk. Connection to each burner is by two short lengths of 12-in. hose arranged at right-angles to each other to permit adjustment of burner position. The burners are counterbalanced, and simple handwheel and screw operated gear is provided for vertical and lateral adjustment.

To reduce furnace down-time by speeding up the withdrawal of port ends for repair purposes on the furnaces and mixers, all connections between port ends and service pipework are permanent and are made through flexible tubing of various types.

Oil burners on the steel furnaces are interchangeable. They are 6½ in. dia. × 20 ft. long, with a 2-in. bore centre tube fitted with an interchangeable 1-in. dia. nozzle, and have a Krause No. 4 atomizer at the rear. The burners are counterbalanced and can be adjusted by handwheel and screw operated gear. Burners on the single-uptake furnaces *C*, *D*, and *E* are held and supported entirely by the burner adjusting gear, which is in the form of a frame hung from the port end top steelwork and balanced. The frame and burner can be raised or lowered as a unit and the

burner can be tilted or traversed as required by hand-wheels and screws.

Reversal of each furnace and mixer is by damper-type valves in the flues. The four dampers are operated together by wire ropes from a single set of hydraulic rack-and-pinion operating gear, carried on a platform slung from the stockbay stage steelwork. Dampers are fabricated from 1½-in. steel plate, heavily ribbed, and slide on water-cooled hematite-iron damper frames set in the flue brickwork. The latter are of double-deck type; an air distribution chamber is built in the brickwork over the junction point of the flues and under valve floor level and is covered with steel plates. Combustion air to each unit is supplied by a Davidson fan with a capacity of 30,000 cu. ft./min. at 5 in. W.G. driven by a 50 b.h.p. 750 r.p.m. motor. The fan is equipped with semicircular inlet control operated manually from the control desk.

Each furnace and mixer is equipped with a twin-drum Spencer-Bonecourt waste-heat boiler, having a capacity of 12,800 lb. of steam per hr. The designed steam pressure is 250 lb./sq. in. with a final temperature of 540° F. Each boiler has its own induced-draught fan, of the Howden vane-controlled type, mounted on top of the boiler drums and driven by a two-speed motor of 81–175 b.h.p. at 730–930 r.p.m.

The oil-storage installation and pump house is situated on the east side of the steelplant building. There are three storage tanks with a total storage capacity of 850,000 gal. Each tank is 40 ft. dia. × 36 ft. high and is fitted with steam coils and a shrouded immersion-type outflow heater. Supplies of heavy fuel oil can be received by road or rail. Road tankers discharge by their own pumps through a steam-heated header into the top of the tanks. Railborne supplies are received in full trainloads of twenty 20-ton rail cars at a time, and usually three or four trainloads are delivered per week. Unloading facilities consist of a pipe range with ten unloading points, having oil-discharge hoses and steaming connections, for steaming and emptying half a train at a time. For weather protection this is covered by a building 216 ft. long. The fuel-oil pump house is located at the north end of the oil-storage site. Oil discharged from rail wagons is passed through filters and then pumped into storage by three Hamworthy 3-in. Rotopax vane-type pumps driven by 15-h.p. motors at 975 r.p.m. Each storage tank has a thermometer, a White Fox pneumatic gauge with indicator in the pump house, and a direct-reading contents gauge. Oil leaves the main storage tanks at a temperature of 70–90° F. and passes along the main pipe range to the pump house. Here it is again filtered and goes through a 5000 gal./hr. primary heater before passing to the circulating pumps at 120° F. There are four 2500 gal./hr. Hamworthy Y.220 gear-type pumps, three driven by 15 h.p. 1460 r.p.m. motors and the fourth by a Greenwood and Batley 13·5 h.p. steam turbine. These pumps deliver the oil to three secondary heaters from which it passes into the 4-in. circulating supply main to the steelplant at a temperature of 240° F. and a pressure of 200 lb./sq. in. Supply and return mains are lagged together with a 1½-in. steam tracer between them, and are carried by a pipe bridge to the steelplant building.

The furnace control stations each carry the controls for two units and are placed between each pair of furnaces or mixers and in line with the charging box benches. All the furnace controls are grouped at these points except the hydraulic valves for tilting, port end retraction, and tapping-side door operation. At each end of the control station is a cabin 9 ft. 6 in. square for the furnace crews, and above there are two cubicles for electrical switchgear. Below stage is a platform slung from the stage girders and reached by a stairway from the stage, giving access to valves and fittings below the control station. The instrument board and control desk (*see* Fig. 4) is divided in the middle and each half carries the equipment for one furnace. Each furnace and mixer is equipped with an extensive range of instruments. Furnace pressure is automatically controlled, all other controls being manual, but provision is made for adding further automatic controls if required.

The following instruments are provided for each furnace:

2 Honeywell-Brown electronic indicator recorders for roof temperature, operated from radiamatic units sighted on the roof through the back wall

Kent furnace pressure recorder-controller and indicator operating vanes on the inlet to the waste-heat boiler fan

Kent indicator-recorder-integrators measuring coke-oven gas, oil, air, and steam quantities

Set of 8 Kent edgewise draught gauges indicating draught pressures throughout the regenerator, flue, and boiler system

Foster two-point regenerator temperature recorder with radiation units sighted on the top checkers

Steam pressure gauge for atomizing steam.

On the mixer instrument panels the roof-temperature instruments are replaced by Bristol recorders for atomizing steam pressure, fuel oil pressure, oil temperature and coke-oven gas pressure, the latter with a safety alarm for low pressures. In addition each panel carries a starter for the combustion-air fan, with push buttons, indicator lights and an ammeter; a furnace reversal indicator shows the sequence of operations required to reverse the furnace and indicates by coloured lights when each operation has been completed.

IRON AND STEELWORKS ENGINEERING

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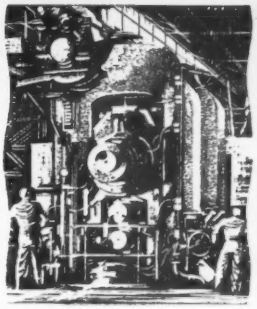

Practical Aspects of the Cold-Rolling of Narrow Steel Strip

By T. W. Hood

SYNOPSIS

This paper deals with the practice at the works of Samuel Fox and Co., Ltd., in the cold-rolling of narrow strip in mild, high-carbon, and stainless steels. Description of the mills is related to the duty for which they have been found most suitable. Hydraulically loaded mills are specially mentioned, with practical problems such as coolant, rolls, roll grinding, roll-neck bearings, etc. The paper concludes with a description of a simple but effective system of automatic gauge control which has proved its worth on a full production basis. 1106

A NUMBER of papers have been written in recent years on various aspects of the theory of cold-rolling dealing mainly with methods of calculation of roll load and torque, taking into account work hardening of the material, roll flattening, the effect of back and front tension, and the coefficient of friction between strip and rolls. No one would deny the importance of this work, especially in the selection and design of a new mill or in the modernization of existing equipment. Practical aspects of cold-rolling, however, especially from the production aspect, have not been dealt with to anything like the same extent, and it is the purpose of this paper to attempt to fill this gap.

Many operations go to make up the work of a cold-rolling plant. In the main these comprise scale breaking, pickling, normalizing, annealing, slitting and shearing, cutting to length, and inspection, in addition to the actual rolling. To deal fully with all these processes would require several papers; consequently it is the rolling process which is mainly dealt with in the paper.

The term 'cold-rolled steel strip' is for marketing purposes limited to a maximum width of 18 in.; material over this width is in general referred to as 'sheet.' This distinction is adhered to in the paper.

Plant and sizes and types of steel rolled vary so widely in the U.K. that the various aspects can best be covered by reference to experience at one plant. Consequently the examples of plant and practice which follow mainly relate to the cold-rolling department at Samuel Fox and Co., Ltd. (Figs. 1 and 2). This plant has a wide range of products, including mild, high-carbon and stainless steels. Widths are mainly up to 10 in. wide; the bulk production of mild steel strip is not undertaken.

HISTORICAL

The works of Samuel Fox and Co., Ltd., were first established in 1842, when Samuel Fox started a wire-drawing business in Stocksbridge, the first product being wire for textile pins. In 1848 he produced solid wire for umbrella ribs; at this time they were mainly of whalebone or cane. In 1852 he patented the trough section for umbrella ribs. This patent (No. 14055 of 1852) gives his method of manufacture:

> ". . . . . narrow strip of steel plate, partially bent into a trough-like form, and this bending I perform by rollers, one having a groove around it and the other a corresponding projection, so that by passing a narrow fillet or sheet of steel through such rollers, the same is bent into the form shown . . . . .
>
> In making ribs of twenty-six inches long I have employed steel wire of No. 13 wire gauge, and having annealed the wire, I pass it between a pair of plain rolls and make it flat, thus producing narrow strips or fillets, bringing it to a width of about No. 6 of the wire gauge. Before passing such narrow strips or fillets through between the rolls above-mentioned for producing the open trough-like form, I anneal them . . . . "

In 1855 he began making flat wire for crinolines, the sizes ranging from $\frac{3}{8}$ to $\frac{5}{8}$ in. by 26 to 29 gauge.

It is difficult to be certain when Samuel Fox started cold-rolling steel strip. At this time he was buying steel from Sheffield. One old account states that together with Mr. James Chesterman he experimented with a pair of rolls which in 1854–5 were transferred to Stocksbridge. It is generally

This paper was presented at the 27th Meeting of the Iron and Steel Engineers Group, held at 4 Grosvenor Gardens, London, S.W.1, on 9th December, 1954. A full report of the meeting will be published in a later issue of the *Journal*.

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Table I
MILLS AT STOCKSBRIDGE

Mill Size			Type of Mill	Max. Speed, ft./min.	Mill Horse-power	Reel Horse-power
Work Roll Dia., in.	Backing Roll Dia., in.	Work Roll Face Width, in.				
12½	..	16	2-high non-reversing	375	75	25
10	..	10½	Two 2-high reversing	200	100	Total
8½	16	12½	Non-reversing semi-continuous	315	150	Total
6½	16	12½		360	150	Total
5½	16	12½		430	150	Total
6½	19	16	Two mills non-reversing: tandem for breaking down; separate for finishing	375	150	25
6	16	7½	Reversing	400	160	25
5·9	16½	18	Non-reversing	350	150	Total
3·35	16½	12½	Non-reversing: semi-continuous with cluster mills below	350	100	Total
5·1	10	11·8	Two cluster mills: non-reversing; semi-continuous (*see* above)	300	40	Total
5·1	10	6·9	Cluster mill, non-reversing	80	40	Total
2·8	10½	11·8	Non-reversing, usually semi-continuous	200	60	Total
5½	11·8	12½		300	50	Total
4	12	7½	Six reversing mills	1500	160	25 or 40
2½	20	7½	Steckel pull-through mill, reversing	1000	..	100

considered that 1854 was the year in which he began to produce cold-rolled strip, first for pens and then for umbrellas, clock springs, and crinolines.

TYPES OF MILL

The types in use at Samuel Fox and Co., Ltd., are outlined below; a list of the mills is given in Table I. Certain other types of mill are also discussed in the paper.

The 2-High Mill

The oldest and simplest type is the 2-high mill, of which there are still a large number in use in the U.K. Such mills are usually fairly slow and are mainly non-reversing. Some of them date back to the time when 80 ft./min. was a typical rolling speed, and have a simple constant-speed drive with a clutch-driven coiler.

This type of mill has two main uses. It is suitable for rolling the thicker gauges of the softer materials, and it is often used for pinch passing (also known as temper rolling) mild steel. On stainless steel it is used for pinch passing (skin passing) to give flatness and surface finish.

The 4-High Mill

Most modern mills are of this type. Compared with a 2-high mill, the use of relatively small work rolls supported by stiff backing rolls enables considerably greater reduction to be taken in one pass and gives greater uniformity of gauge across the width of the strip. The wider, thinner, or harder the material, the more pronounced these advantages become.

There are many examples of 4-high mills arranged as either single-stand non-reversing, reversing, or tandem mills. Single-stand non-reversing mills are most suited to short coils, as all the strip passes through the rolls. Consequently they are very useful for breaking down; methods of operation are either to give an individual coil the full number of passes before rolling the next, or to use batch rolling by giving the first pass to a number of coils, then adjusting the rolls and giving all coils the second pass, and so on. With good handling equipment the batch system is the most efficient.

The reversing mill requires a shorter interval between passes, and can use higher back tension for all passes after the running-on pass. It has one disadvantage, which is quite unimportant for very long coils, namely that the ends of the coil remain on the drums and so are not reduced. One example is known of reducing the loss in yield by allowing the back end to leave the reel after each pass, so that only a very short length does not pass through the rolls. Quick entry into the slot in the drum involves very little loss of time.

Tandem Mills

Table I includes only one reference to a tandem mill; two of the stands are widely spaced and each has an uncoiler and a coiling reel, but the drive is so arranged that they can be run in tandem. The usual type of tandem mill for narrow strip consists of three or four 4-high stands (generally four), closely spaced. Such mills are mainly used for low-carbon steel. The main justification for this type of mill is high output, with reasonably long runs of a size. Speeds are usually higher than with a reversing mill; for narrow strip 1200 ft./min. is often regarded as typical for a fast reversing mill, though Table I shows six mills nominally capable of 1500 ft./min. By comparison the most recent tandem mill in this country, a 10½ in. and 30 in. by 18 in. 4-stand 4-high mill, has a maximum finishing speed of 2100 ft./min.

This type of mill is also used for stainless and high-carbon steels; there are examples with moderate speeds of 450–650 ft./min.

The Cluster Mill

To give both vertical and lateral support to the work rolls the cluster mill was developed. Three cluster mills are shown in Table I. All three have 5-in. dia. work rolls; because of this they show no advantage over a 4-high mill. Simplification of work-roll chocks is outweighed by duplication of backing rolls, bearings, and screws. With a 5-in. roll the line of centres of work roll and backing roll is approximately 45°, so that the load on the backing roll bearings is 0·7 of what it would be in a 4-high. Below 3⅞ in. dia. the line of centres would exceed 60° from the vertical, giving a bearing load greater than on 4-high.

The two 12-in. cluster mills are used to follow a 4-high mill in a semi-continuous train. As the cluster mills are of relatively light construction, most of the reduction is done by the 4-high. The clusters, however, are good mills for finishing and give good strip shape.

The theoretical limit of backing to work roll diameter is 4 : 1, at which ratio all four backing rolls

would foul each other. These mills are rather old examples and have a 2 : 1 ratio. Recent cluster mills have up to a 3 : 1 ratio.

Work-roll alignment is not a problem once the screwdown has been correctly set. Backing rolls are matched in diameter to keep the line of work-roll centres vertical.

The Steckel 4-High Mill

This is an early example of the pull-through 4-high reversing mill, with only one motor driving whichever reel is acting as the on-coiler. Drive to the off-coiler is disengaged by a pawl and ratchet-wheel device, and a friction brake applies some degree of back tension. The on-coiler rotates at a constant speed (according to the speed setting) with no compensation for coil build-up, so that strip speed increases during a pass. As they are not driven the work rolls need not be matched in diameter. Work-roll changes average 13 in 17 shifts. The reels are mounted underneath the pass-line rollers; strip is removed from the mill by recoiling.

A straight mineral oil is used both as rolling oil and as lubricant for bearings and coiler gearing. Such an oil is a poor coolant, and to prevent undue overheating the pass-line rollers are hollow, with internal water-cooling. The position of the reels ensures that the strip has a long arc of contact over these rollers. Without this cooling it has been found that thermal expansion of the rolls makes it very difficult to maintain strip shape. Some more recent versions have the coilers on either side of the mill, as in a normal 4-high.

This mill has a maximum speed of about 1000 ft./min., and is normally run at about 750 ft./min. (max. coil build-up). The reduction per pass is limited by the fact that all the power is applied by strip tension.

The duty of this mill is mainly to roll thin mild steel, starting size 0·080 in., down as low as 0·004 in. without annealing. The normal pass schedule is to give 15% reduction per pass down to 0·007 in. (15 passes), except that over 5 in. wide the first four or five passes are only 10%. Below 0·007 in., reduction is 10% except for finishing. Occasionally 20% reductions can be given on strip below 5 in. wide down to 0·026 in., reverting then to the normal schedule. To compare this mill with an equivalent conventional 4-high, a typical output on $5\frac{7}{8}$ in. × 0·004 in. is 9–10 cwt. per shift, coil weight being 10 cwt. One of the 4-in. and 12 in. × $7\frac{1}{2}$ in. reversing mills gives more than a 50% higher output on this size. This mill also rolls 0·50% and 0·70% C strip, reductions for these steels being standardized at 10% per pass.

Among the other unusual features of this mill is the use of a motor-driven wedge-type screwdown. Roller side guides are used except for very light gauges. Reduction is measured by an elongation meter, which compares the speeds of the entry and delivery pass-line rollers.

This mill has run for 22 years and has given very little trouble.

ROLLING PRACTICE

In outline, the system adopted for the main product groups is as follows.

Mild Steels

The heavier gauges are hot-rolled to five gauges thicker than the finished size required. Thin mild steel is usually hot-rolled to 0·080 in. After scale breaking by staggered rollers and continuous pickling it is rolled to size, slit, and annealed if required dead soft.

Pinch passing is done mainly on a 2-high mill, usually with a reduction of 0·00025 in. to 0·0005 in. Finished thickness is mainly 30 gauge and thinner. Strip required to finish to a given temper is given an intermediate anneal at the appropriate gauge, and then slit after final rolling.

Carbon Steels

The main qualities are 0·50%, 0·70%, 1·00%, and 1·25% C steels, in widths of approximately 6 in.

The 0·50% and 0·70% C strip, hot-rolled to 0·080 in., goes first for scale breaking, pickling, and bright annealing. It is then rolled to size with usually one intermediate bright anneal, maximum reductions being 55% to 0·036 in., followed by 66% reduction to 0·012 in., this being the thinnest gauge normally required. It is then slit and given a final bright anneal.

The 1·00% and 1·25% C strip is hot-rolled to 0·096 in. and goes for normalizing, scale breaking, pickling, and annealing. It is then rolled to finished size with several intermediate anneals, the reductions between anneals starting at about 30% and rising to rather more than 50%. The reductions are kept low until the steel is fully spheroidized. Care is required as this material is prone to edge cracking.

Stainless Steel

Starting sizes are up to 9 gauge, according to quality and width. Ferritic and martensitic steels are pot annealed, then all are given a scale-breaking pass of 8–10% before descaling. They are then rolled to 0·092 in., bright annealed, ground if required, and rolled to finished size with reduction of 4–5 gauges between intermediate anneals.

ALLOCATION OF DUTY TO MILLS

Like many others, this is a long-established cold-rolling plant which has from time to time been modernized by the introduction of new equipment. At any one time, including the present, it consists of plant of various ages, and the wide range of products is allocated to the mills in the most suitable way for balanced and economic production. One or two of the older mills are barely economic, but cannot be dispensed with until considerable additional capacity is installed. The following general picture of the main duty of each mill gives some indication of the work for which each is most suitable.

(i) The 5·9 in. and $16\frac{1}{2}$ in. × 18 in. non-reversing and 6 in. and 16 in. × $7\frac{1}{2}$ in. reversing mills are the heavy roughing mills and are mainly engaged on the first two rollings of high-carbon strip, with a little mild steel in the thicker gauges

(ii) The two 3-stand semi-continuous trains are used for intermediate rollings of high-carbon strip, and finishing these qualities in the thicker sizes. They seldom roll below 0·010 in.

(iii) The six reversing mills, 4 in. and 12 in. × $7\frac{1}{2}$ in., are engaged on the last two rollings of thin

high-carbon strip, mainly for razor blades, approximately three mills to each rolling. One of these mills also rolls a quantity of thin mild steel

(iv) The Steckel mill is engaged on thin mild steel down to as low as 0·004 in., with some 0·70% C strip mainly finished between 0·012 in. and 0·017 in.

(v) The two small non-reversing 4-high mills, 2·8 in. and 10¼ in. × 11·8 in. and 5¼ in. and 11·8 in. × 12¾ in., are used for the final rolling to between 0·008 in. and 0·012 in. of mild steel which has been reduced to 0·024 in. on one of the 2-high mills. They are also occasionally operated separately for pinch passing mild steel

(vi) The two non-reversing 6¾ in. and 19 in. × 16 in. 4-high mills are largely devoted to stainless steel, with a little wide heavy-gauge (0·030–0·060 in.) mild steel

(vii) The small cluster mill, 5·1 in. and 10 in. × 6·9 in., is mainly engaged on high-carbon strip, such as for feeler gauges, and oddments

(viii) The 2-high mills are used for heavy-gauge mild steel, 0·50% C strip down to about 0·030 in., and pinch passing.

HYDRAULICALLY ADJUSTED MILLS (Fig. 3)

Experience has been gained over several years with seven 4-high reversing mills of this type. A main factor in the adoption of this method of roll adjustment was the requirement for a rigid mill standardizing on approximately 6 in. wide strip. The roll barrel length is 7½ in. (7 in. + two ¼ in. chamfers), and with such close spacing between housings hydraulic adjustment is both cheaper and easier to fit than a motorized screwdown.

In these mills hydraulic rams are let into the bottom of the housings; after the strip has entered, the load is applied by a hand-operated pump through non-return valves. Pressure can be applied to both sides at once or to each side separately, and can be released in the same way. When rolling the rolls are supported on a closed column of oil, which gives the same order of rigidity to the mill as if screwdown gear were used. This method of applying the load to the mill is quick and sensitive.

When changing rolls the release valves are opened and the bottom roll sinks under its own weight. It would be an advantage to have a motor-driven pump for raising the bottom roll again to the working position, though this modification has not been made. For rolling, the hand-operated pump is fully satisfactory and probably is more sensitive in adjustment than if motor-driven.

Working pressure on the rams ranges between 500 and 1500 lb./sq. in., and is usually about 1000 lb./sq. in. Loss of pressure during a pass due to oil leakage is rare. Occasionally rams or cylinders have become scored, owing to ingress of grit or small particles of steel breaking from the edge of the strip. This can also give trouble in preventing the bottom roll from sinking when pressure is released. By fitting protective skirts above the rams and using brass rams in chromium-plated steel cylinders, the difficulty has been largely eliminated.

Two pressure gauges, one for each cylinder, give a measurement of roll load on each side of the mill. Miscellaneous features of these mills include air-operated wipers and an automatic stop in the event of strip breakage. The pass-line rollers are mounted on a pivoted bracket and strip tension holds them down against a spring. Removal of strip tension allows them to lift to operate a switch which stops the mill (Fig. 4).

Although mainly engaged on high-carbon and thin mild-steel strip, these mills are efficient units for the production of medium-gauge mild-steel strip. For example, in the production of strapping, 4¾ in. × 0·048 in. strip is reduced in three passes to 0·014 in., at the rate of about 10 tons a shift, coil weight being 7½ cwt. Collapsible drum-type coilers are used on such material. Rolling speeds are 600–700 ft./min. for the first pass, and 800–1000 ft./min. for the remainder.

WORK-HARDENING FACTORS

Cold-rolled steel strip is often required to be within a specified range of ultimate tensile strength. It is found that tensile strength increases almost linearly with percentage reduction, and a simple formula is frequently used to calculate the reduction and hence the starting size of the strip. According to this formula, the tensile strength in the work-hardened condition is obtained by adding to the tensile strength before cold-rolling a quantity which is the percentage cold reduction multiplied by a work-hardening factor. Within a range of reduction of 20–80% this is accurate to within ± 5%. It applies both to rolling from the hot-rolled size (whether as-rolled, normalized, or annealed) and to rolling after an intermediate anneal, provided that the correct initial value of tensile strength is used. This is found to vary considerably after an intermediate anneal according to the amount of previous cold work. Cold finishing in a hot strip mill with no subsequent softening treatment also affects the initial figure.

The work-hardening factors for a number of steels are given in Table II.

WORK-ROLL DIAMETER

If other dimensions remain unchanged it is well known that an increase in roll diameter causes an increase in roll load, not only because of geometrical considerations, but also because of the flattening of the rolls. Small rolls are advantageous when rolling thin hard strip, because they can give heavier reductions per pass and larger total reductions between anneals.

Because of roll flattening there is a limit to the reduction which can be achieved in a single pass by forcing the rolls closer together. A set of curves from which this maximum reduction can be quickly estimated is given by Sims.[1] As he points out, it is much more dependent on the coefficient of friction between rolls and strip, which is not accurately known, than on the yield stress of the material or the ratio of roll radius to initial strip thickness. Recently a practical problem arose as to whether a certain mill could roll a particularly hard thin strip; calculation showed it could be rolled with 15% reduction per pass if the coefficient of friction were 0·055, but could not be rolled if the latter figure were 0·07. It was finished with a 2% reduction.

Fig. 1—Cold-rolling department, Stocksbridge, 1926

Fig. 2—Cold-rolling department, Stocksbridge, 1954

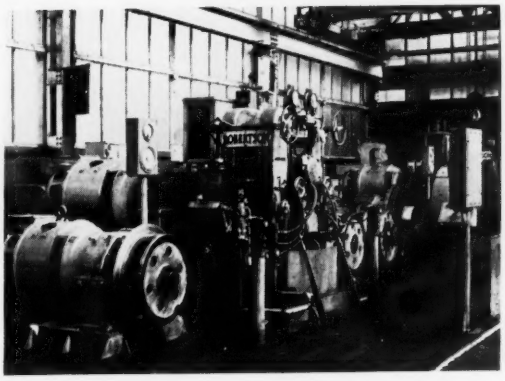

Fig. 3—Hydraulically loaded mill, 4 in. and 12 in. × 7½ in.

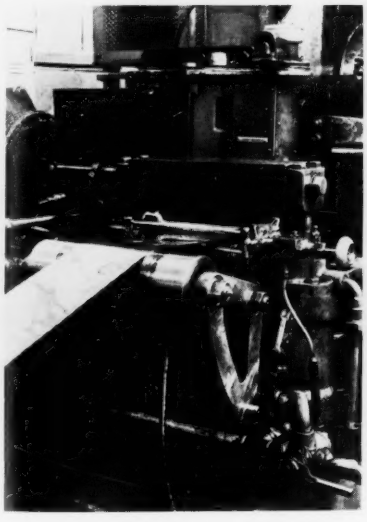

Fig. 4—Automatic stop and spray pipes for atomized rolling oil

Fig. 5—Severely spalled work roll

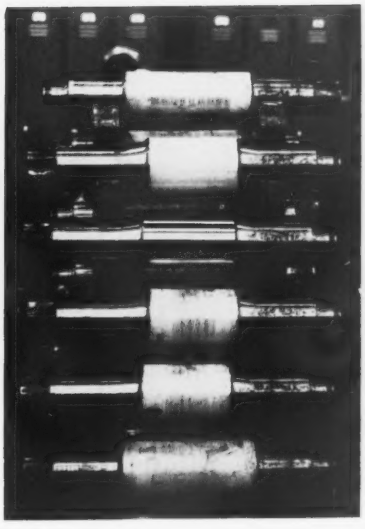

Fig. 6—Tapered roll necks

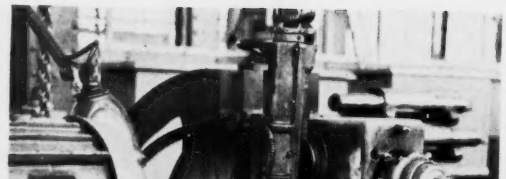

Fig. 7—Superfinishing a work roll

Fig. 8—Transport of coils in a stillage

Fig. 9—Pullthrough-type slitting machine, with tungsten carbide cutters

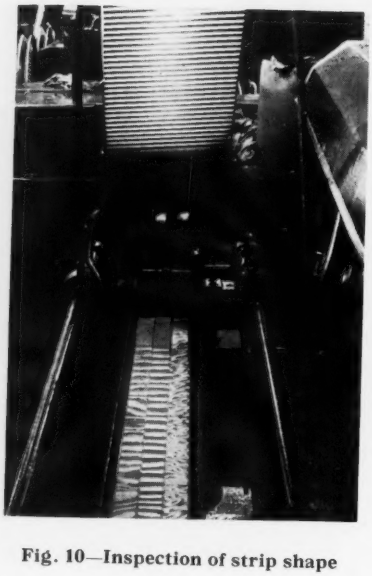

Fig. 10—Inspection of strip shape

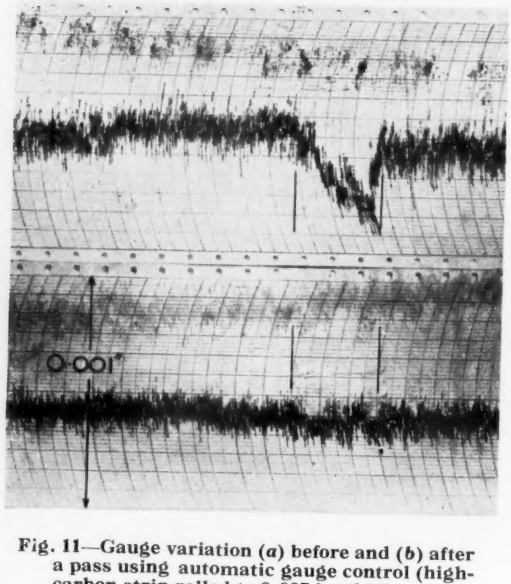

Fig. 11—Gauge variation (*a*) before and (*b*) after a pass using automatic gauge control (high-carbon strip rolled to 0·007 in. thick)

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To face p. 193]

The use of small-diameter work rolls forms the basis around which several special types of mill have been developed; three of these will be briefly described later.

In a 4-high mill the minimum diameter of the work roll is limited by several factors. The pinion diameter must be large enough to transmit the required torque, the length/diameter ratio must be sufficient to withstand lateral bending, and, especially for mills threaded under load, the angle of contact must not be excessive.

If the rolls are not directly driven the limitation due to driving torque is removed. Those 4-high mills which use either no drive to the rolls or indirect drive from the backing rolls have smaller-diameter work rolls for a corresponding width than a conventional 4-high.

Support against lateral bending is obtained in the cluster mill, although in a mill with two work rolls and four backing rolls the limitation in diameter of the backing rolls usually prevents the length/diameter ratio from being higher than can be obtained in a 4-high mill. Furthermore, these mills usually have directly driven work rolls.

Where very small-diameter work rolls are required, a multi-cluster mill removes this limitation of the simple cluster arrangement, because the two rolls in contact with each work roll are themselves supported by larger backing rolls, as in a Rohn mill, or by roller races as in a Sendzimir mill. Depending on the proportions of the work roll, either one or two sets of intermediate rolls are used. The work rolls are so small that drive is applied to the backing rolls.

Some features of using very small work rolls are:

(i) From contact-angle considerations, the percentage reduction may be less when the strip is thick than later in the rolling

(ii) Such rolls have little thermal capacity, so that their expansion can give rise to problems in strip shape.

STRIP TENSION

The old idea about tension was that only sufficient should be used to coil the strip evenly as it left the mill; although it is possible to work on heavy-gauge material in this way, light gauges require an increase in front tension to produce flat strip. Back tension is not essential when rolling heavy-gauge strip on slow mills, but with light gauges the side guides on the entry side are not able to ensure that the strip remains central in the rolls, and back tension is used for this. Usual practice is to apply back tension on a single-stand one-way mill and on the first pass of a reversing mill, by a combination of a friction brake on the uncoiler and a pressure wiper on the entry side. Because of the difficulty of controlling the strip under these conditions the speed of the first pass on the small high-speed reversing mills is limited to 600–700 ft./min.

A roller-leveller unit, for straightening and feeding the front end of a heavy-gauge coil, is another means of applying back tension to the first pass. These units are not used at Stocksbridge.

Modern reversing and tandem mill practice is to use high tension. The effect of this on reducing the roll load is of considerable importance for rolling light gauges on large-diameter rolls, but is less so with small rolls. With small rolls, however, high tension is used, and is often relied on to hold the strip central.

Tensions used range up to 40,000 lb./sq. in. and can be as high as 60,000 lb./sq. in. At Stocksbridge front tensions up to about 35,000 lb./sq. in. are used; the ratio of back to front tension on the reversing mills usually lies between 0·25 and 0·5.

Especially with material prone to edge cracking, it is desirable to roll with slightly long edges, to give reduced edge tension, except when finishing.

The older mills have adjustable cone-type slipping clutches, for driving the coiling drum from the mill motor. Such a drive is cheap and simple but, being essentially a constant-torque device, it causes the tension to fall off as the coil builds up, except as adjusted by the operator during a pass. It is reasonably satisfactory in operation, as the mills using it are relatively slow. One of these mills has a maximum speed of 450 ft./min., with a coil build-up of approximately 2·2 : 1. For this mill the tension available is lighter than is desirable.

Three of the mills have a differential gear which divides the power from the motor between the rolls and the coiler drum. About 25% of the total power is applied to the coiler, with facilities for a small variation of tension.

Four of the pre-war mills and all the post-war mills have individual motor drive to the boiler drums with Ward-Leonard speed control and automatic tension control.

At constant strip speed the requirement of constant tension means that the horsepower of the coiler motor must be maintained constant independent of coil build-up. With speed varied by armature voltage control, constant tension is obtained with

Table II

WORK-HARDENING FACTORS

Material	Work-Hardening Factor
Carbon Steels	
O.H. dead soft (silicon trace)	0·35
„ „ „ (silicon solid)	0·45
„ medium and high carbon	0·50
Bessemer, dead soft	0·50–0·55
Stainless Steels	
Martensitic (0·10% C, 13·0% Cr)	0·35
Martensitic (0·20–0·40% C, 13·0–14·0% Cr)	0·45
Ferritic (0·10% C, 17·0% Cr)	0·40
Austenitic 17·5% Cr, 7·0% Ni	1·10
„ 18·0% „ 8·0% „	1·05
„ 19·0% „ 8·0% „	1·03
„ 20·0% „ 8·0% „	0·98
„ 21·0% „ 8·0% „	0·93
„ 18·0% „ 9·0% „	0·97
„ 17·5% „ 10·5% „	0·86
„ 19·5% „ 10·0% „	0·79
„ 21·0% „ 10·0% „	0·75
„ 18·0% „ 12·0% „	0·75
„ 12·5% „ 12·5% „	0·78

reasonable accuracy if the armature current is held constant, due correction being made for voltage drop across the armature resistance and for acceleration torque.

Without going into details of the electrical circuits it may be mentioned that among these mills there are examples of three types of automatic tension-control devices:

(i) A *carbon pile*, effective over a limited tension range (5 : 1 for the mills in question)
(ii) *Contactor control*, which gives an intermittent correction; for example if current is set to 45 A., it is maintained during coil build-up between about 40 and 45 A.
(iii) *Thyratron control*, giving an overall range of just below 7 : 1; maintenance on this is simplified by the provision of spare panels.

COILERS

The drum-type coilers fitted to cold mills are of two main types, collapsing and solid. Collapsing drums are of many types, which can be subdivided into those operated by rotation of the shaft relative to the drum (as in a cam type) and those which use an axial movement of the shaft, using toggles, wedges, or cones. Of the several types used at Stocksbridge, the newer mills have cone-type coilers, without grippers, the strip being held by insertion in the gap between segments.

For large coils of thin strip, collapsible drums tend to distort, and apart from this they are never truly cylindrical when expanded so that they mark the strip. For this reason solid drums are used when the strip is very thin, (e.g. with thin high-carbon strip). In the final rolling the strip is held by friction, but in the previous rolling simple slots are used. No belt wrappers or ' blockers ' are used at Stocksbridge; the time saved would be very small in relation to the rolling time for precision finishing.

The disadvantage of solid drums is that the strip can only be removed by recoiling. This recoiling operation has, however, one advantage: tension is low so that an opportunity is given to inspect the strip shape as compared with the apparent shape when being rolled under high tension.

Rolling with thick rims on collapsible drums is an alternative which avoids the need for recoiling after the final pass, as the coil can then be transferred directly to the slitting line. With 6-in. wide strip, however, a rim $1\frac{1}{2}$ in. thick and 28 in. inside dia. distorts if the coil is allowed to cool on it.

ROLLING OILS AND COOLANTS

Because of cooling problems the use of mineral oil alone is limited either to low-speed mills or to high-speed mills taking light reductions; otherwise soluble oil is used. A change from rolling oil to soluble oil on the $5\frac{1}{4}$ in. and 16 in. $\times$ $12\frac{3}{4}$ in. mill, rolling work-hardened high-carbon steel, enabled the speed to be increased from about 250–300 ft./min. up to the maximum available of 430 ft./min.

An important requirement for either type is freedom from staining during subsequent annealing. For most purposes soluble oil is applied alone, but for certain mat finishes a small amount of mineral oil is sprayed on the strip from an atomizer.

A well-known proprietary brand of soluble oil is used, in the form of an emulsion consisting of 10% oil and 90% water. The amount applied to each mill is nominally 15 gal./min., which compares well with a simple empirical formula, namely that the rate of flow should be $\frac{1}{2}$ gal. per minute per inch of total contact width. This width includes contact of work rolls with both strip and backing rolls. Another formula is that flow (gal./min.) should be one-tenth of main motor horsepower (160 h.p. for the small reversing mills).

A central system is used to supply the whole mill bay; at present it feeds seven mills, the rest being on mineral oil.

Central Cooling System

The main tank holds 11,000 gal. and is located in a cellar. Oil is circulated by two 300-gal./min. pumps, one being a standby. Temperature is maintained at 98° F. by a steam heater or water cooler, as required, with thermostatic control. Feed pressure at the mills is held steady by a header tank 26 ft. above floor level.

Return to the tank from the mill sumps is by gravity, oil pipes being laid in ducts below floor level. In the tank it passes through a gauze strainer, around a grid of magnetic rods, and through five canvas-bag filters.

A daily check of the oil content is made, and the system is topped up with oil or water as required to maintain the 10% concentration. Make-up of soluble oil averages 45 gal. a week. The tank was first drained for cleaning after three years' operation.

Scum is skimmed into a sump, from which it is discharged by a float-operated pump into a large receiving tank. From this it is run into one of two tapered-bottom 500-gal. steam-heated tanks together with dilute sulphuric acid; 24 hr. are allowed for splitting into water and acidified soluble oil.

ROLLS

Rolls are of forged steel, mainly of the 1% C, $1\frac{3}{4}$% Cr type, hardened and tempered to give a Shore hardness of 95–100° on the work-roll barrel. Backing rolls are in the region of 65–70° Shore. The total life is approx. 0·45 in. on work rolls and 0·5 in. on backing rolls, varying somewhat for the different mills.

The main problem with work rolls is that of spalling, which is a common trouble with reversing mills using soluble oil. The stresses to which they are subjected are most complex, being a combination of

(i) Internal stresses due to the hardening operation
(ii) Alternating stresses due to the rolling load, occurring twice per revolution in a 4-high mill
(iii) Steady and alternating thermal stresses: the surface is heated when in contact with the strip and cooled rapidly both by conduction into the body and by the coolant.

Examination of the fracture in a spalled work roll reveals the typical pattern of a fatigue failure (Fig. 5). The source of origin on the small rolls in question appears to be $\frac{1}{8}$–$\frac{3}{16}$ in. below the surface and often, but not always, at a position corresponding to the edge of the strip.

Little is known fundamentally of the cause of these failures. Some may be due to a 'pile-up' in the mill, especially when a new mill is being run in. At Stocksbridge they have occurred in epidemics, which for some reason lasted about two months in a year. After reducing them to an average as low as 1½ rolls per mill per year, a further epidemic occurred when the output of the mills was increased. Raising the temperature of the soluble oil above the figure given appears to have greatly alleviated the problem. It is also known that the rolling schedule affects the frequency of spalls; for example, the rolling of hard high-carbon strip before the last anneal gives rise to more spalling than the rolling after this anneal. Stress relieving after use is used in some works, by holding at 100–120° C. in water or oil for about 8 hr. The number of rolls in circulation at Stocksbridge has so far prevented the use of this method.

With a mill using 5¼ in. × 12¾ in. work rolls, rolling only 6-in. wide strip, tapering the barrel down to the neck avoided spalling. It was necessary to keep a good radius at the ends of the barrel (Fig. 6).

Tungsten Carbide Rolls

The main attraction of tungsten carbide for work rolls is the greatly increased life between grinds. It is claimed that such rolls have up to 50 times the life of hardened steel rolls, which more than compensates for the higher capital cost. Application of solid tungsten carbide rolls on mills with driven work rolls is difficult because the torque which can be transmitted through the necks is very limited. The use of tungsten carbide sleeves on a steel mandrel involves the danger of bursting the sleeve as the roll becomes hot in use, the coefficient of thermal expansion being about half that of steel. This method is, however, used for wire-flattening mills (e.g. on rolls 4 in. dia.) with internal water-cooling of the mandrel. Another method is to use a mandrel with the same coefficient of expansion as the carbide.

As far as is known the main use of tungsten carbide rolls is in mills where the work rolls are not directly driven, such as the Sendzimir, Steckel, and C.M.P. mills. For example, they are used on stainless-steel finishing passes on a Sendzimir mill type ZR 23–25 and on various products for the 3 in. × 10 in. work rolls of a C.M.P. mill. Excellent finish is obtained, and the low coefficient of thermal expansion reduces the effect of roll-temperature changes on strip shape.

A further advantage of tungsten carbide is that it has a high Young's modulus, about twice that of steel, so that roll flattening is reduced and with thin hard material both roll load and the limiting thickness for a given reduction are accordingly lower.

Some carbide rolls have a surface showing cloudy patches which, although stated not to be due to porosity, leave a corresponding cloudy pattern on the strip surface. These rolls are suitable for strip where surface finish is not of prime importance.

Roll Changing

With high-carbon strip it is necessary to change work rolls frequently. In the roughing rollings, when reducing down to about half the original thickness, the maximum number of passes between roll changes is about 45. As the coils get thinner and longer this number is reduced, until for the final rolling changing is done after about eight passes. It is important to keep the roll-changing time to a minimum. On the small finishing mills the average time is 20 min.

Backing-roll changes vary considerably in their frequency, some of the roughing mills being changed only once or twice a year whereas the small finishing mills are changed every few weeks. No regular schedule of changing is used, though this is known to be practised elsewhere, but care is taken to examine the rolls at frequent intervals so that they are changed before a small spall becomes large and deep. As far as possible backing rolls are changed at weekends.

ROLL GRINDING

Particularly when finishing high-quality strip, it is necessary to grind the surface of the roll barrel at frequent intervals. This is carried out on special roll-grinding lathes; for small rolls grinding is done on centres, using steadies as required.

Frequently coarser grit wheels are used for rough grinding and fine grit for finish grinding, but at Stocksbridge, except for a few badly marked rolls, it is the practice to use only one wheel. This is a 400-grit silicon carbide resinoid-bonded wheel, 2 in. wide × 26 in. outside and 12 in. inside dia. with a surface speed of about 4400 ft./min. For metal removal in rough grinding the wheel surface is opened by dressing; for finishing the wheel is allowed to make up. The reduction in diameter at each grind is approx. 0·002 in. For the numerous 4 in. × 7½ in. work rolls the time required is normally 30 min.—10 min. roughing and 20 min. finishing.

Eccentricity is almost always less than 0·0001 in., as checked by a dial gauge when the roll is in the grinder. Diameters of a pair of driven work rolls are matched to 0·0001 in.

Surface finish, as measured parallel to the roll axis by a Talysurf machine, is consistently 0·7 micro-inches (centre-line average). On removal from a mill the corresponding figure, apart from roll marks, is 1·5–2 micro-inches for a finishing roll.

The number of rolls ground in a week is over 700, of which about 320 are 4 in. × 7½ in. work rolls for the six post-war finishing mills. These figures emphasize the need for quick roll changing; they represent for each of these six mills an average of 1–2 changes per shift, according to the class of work.

Superfinishing of Rolls

This method of finishing by honing has been tested, using an oscillating head mounted on a lathe. Superfinishing of a finished-ground roll was abandoned because the results did not justify the extra operation. Good results have, however, been obtained by using superfinishing on rough ground rolls: after 10 min. roughing, a 4 in. × 7½ in. roll is transferred to the superfinishing machine and after 7–10 min. the roll is ready for use. The amount of metal removed is negligible and the roll camber is not affected (Fig. 7).

Roll speed is approx. 200 ft./min.; traverse begins at 3 ft./min. and is reduced to 2 ft./min. for the last few traverses. The stone is fibre-bonded 180-grit

silicon carbide, bearing with a pressure of 17½ lb./sq. in. The stone oscillates axially along the roll with a $\frac{3}{16}$-in. stroke, starting at about 200 oscillations per minute and slowing to the minimum available.

This system is now in regular use, mainly to supplement the existing roll-grinding capacity. The appearance of a superfinished roll is slightly duller than that of a roll finished by grinding, but the measured surface finish is very similar, varying slightly up to occasionally twice as rough as the ground roll.

There is some evidence that the superfinished rolls last longer between dressings than ground rolls. On a breaking-down rolling, tests showed an average of almost a 50% increase in life, but on final rolling little difference was found, possibly because mechanical damage (roll marks) has a large influence on roll changing at this stage.

ROLL-NECK BEARINGS

Backing Rolls

Most of the older mills have roller-bearings on the backing rolls, some shrunk on and others with a sliding fit. There are no examples of oil-injection mounting, although one of the mills with shrunk bearings is being modified to this type. Lubrication is either by oil or grease. Both are satisfactory, though the newer mills use grease.

Two of the post-war small reversing mills have roller-bearings, with a sliding fit on the necks. The first sign of bearing-race failure by pitting over part of the circumference of one of the outer races came after two years' continuous running. This bearing is still in use, six months later, by keeping the pitted area out of the loaded arc when turning the outer races 120° in the chock every three months. Two problems have arisen in use. Because of wear and pitting of part of the roll neck it was found necessary to drill each neck to provide positive lubrication between neck and inner race. To reduce the tendency of soluble oil to enter the bearing through the labyrinth seals, it was considered advisable to groove the chock to accommodate a synthetic-rubber ring, bearing on the shoulder of the roll.

The other post-war mills have oil-film backing-roll bearings. These have behaved well except for one disadvantage, namely occasional difficulty of starting from rest under full load. The clearance between neck and bearing was established by experiment when the first two of these mills were installed at 0·017–0·018 in. on a neck diameter of 8½ in. At 0·002 in. per inch diameter this is rather more than the figures usually quoted. To fit roller-bearings to those rolls involves reducing the neck diameter to 7⅜ in.

Work Rolls

Bearing types include bronze, white-metal, and two mills with roller-bearings.

The high-speed mills have white-metal bearings, flood-lubricated from the circulating system for the backing rolls. The main problem with these bearings is oil loss through the seals, mainly due to damage arising from frequent roll changing. The bearings last about six weeks before they wear oval to such a degree as to affect the alignment of the work rolls. This gives rise to excessive end thrust on the work rolls and unequal pressures on the two sides of the mill.

To overcome the loss of bearing oil, fabric bearings have been used. These were lubricated from the soluble-oil supply, so that leakage involved no loss. Their life averaged about one month. Examination after failure showed a tendency to charring, the soluble oil being probably too warm to give sufficient cooling. The use of cold water avoids charring but leakage dilutes the soluble oil. Leather seals, chevron packings, and synthetic rubber seals were used, the latter being probably the best. Fabric was abandoned because of the need to be certain that no soluble oil could reach the strip on qualities rolled with rolling oil only.

One of these mills has now been converted to multi-row cylindrical bearings with oil-mist lubrication.

MECHANICAL HANDLING

The importance of reduced handling time is most marked when either short coils or high speeds are used, for otherwise the ratio of rolling time to handling time is unduly low.

To a large extent strip width is standardized at about 6 in. wide, in coils weighing ½ ton. Eight such coils make up a charge in a bright-annealing furnace, and the handling system in the plant is based on a ' pot ' of eight coils.

Transfer between annealing bay, mill bay, etc., at Stocksbridge is by stillages known as ' baths,' which have a bottom in the form of half a cylinder, with partitions to take eight coils. These are transported by trucks (Fig. 8).

Handling between baths and mills, etc., is by overhead crane and wire-rope slings. The main bay has 19 mills and is served by three 5-ton E.O.T. cranes. There is not sufficient gangway width in this bay to permit the use of lift trucks equipped with booms. Certain parts of the plant have individual hoists on swinging jibs.

Most uncoiling stands consist of light collapsible drums with three segments; for feeding single-pass mills, such as the first stand of a semi-continuous train, double uncoiling stands are used, pivoting about a vertical centre, such that the drum in line with the mill is working while the other is being loaded.

In the heavier gauges the strip is coiled on collapsible drums and removed by crane. The mills rolling stainless steel are equipped with coil ejectors and horizontal unloading arms. Light gauges are coiled on solid drums, and are then recoiled on rims placed on the collapsible drums. These rims are necessary to prevent the coil distorting under its own weight after removal.

Increased output from the finishing mills points to the desirability of eliminating the operation of recoiling on the mill. On a reversing mill with the recoiler between the uncoiler and the main coiler, and working to a four-pass schedule, recoiling can be (and is) done during the first pass of the next coil. Strip from the uncoiler passes over the recoiler and nearside coiler. With a three-pass schedule this can only be done if uncoiler and recoiler are duplicated

on each side of the mill. Detachable solid drums, with separate recoiling facilities, are used successfully elsewhere and their adoption is being investigated.

SLITTING

Rotary gang slitters are used for slitting to narrow widths and for edge paring. Thirteen machines of various capacities are installed, a number of these being designed in the works for special requirements. Speeds vary according to gauge and type of steels and go up to 700–800 ft./min. on mild steel in thin gauges. The older machines have driven cutters, but seven machines have pull-through heads, the cutters rotating on either roller-bearings or tungsten carbide centres. More accurate results are obtained from the pull-through slitting machine, together with longer cutter life between grinds. The latest machine to be installed, a Fox design for high-carbon strip, is of the pull-through type. Designed maximum speed is 500 ft./min.

The materials used for cutters are 14% and 18% W steels, and tungsten carbide. Tungsten-steel cutters are initially $7\frac{1}{2}$ or $8\frac{1}{2}$ in. dia., depending on the machine, scrap size being $5\frac{7}{8}$ and 7 in. respectively. They are built up on a mandrel with spacers as required. Clearance between top and bottom intermeshing cutters is best found by practice to suit the material being slit, its thickness, and its tensile strength. Too much clearance tends to cause fash in the slit strip, whilst insufficient clearance reduces the cutter life. The cutters are intermeshed 0·002–0·003 in. plus the actual thickness of the material being slit. This increases the life of the cutter and gives a better edge to the slit strip.

Wooden entry and stripping boards are fitted between the cutters, and the setting of these boards is an important feature of the slitting operation. These boards prevent 'dishing' of the strip and so keep it within the desired tolerance on width.

Tungsten carbide cutters are used only on standard-width material, the throughput of which justifies the high initial cost—e.g. razor strip (Fig. 9). Life between grinds is 30 times that of the tungsten-steel cutters. Diameter when new is 5 in. and scrap size 4 in. They are built up on a mandrel and kept as a unit for their working life; 400-grit diamond-impregnated wheels with a resinoid bond are used for grinding. An average of 0·0035 in. is removed per grind.

Figure 10 shows 3 lengths of slit strip on an inspection bench. The overhead light is striped, and the regularity of reflection of the stripes from the strip surface indicates its flatness.

ANCILLARY PLANT

The ancillary plant used in conjunction with the mills listed in Table I includes:

- 2 continuous normalizing furnaces for hot-rolled high-carbon strip
- 1 scale breaker
- 1 continuous pickle line, plus batch pickling facilities for stainless steels
- 26 pot-type electrically heated bright-annealing furnaces, all of 4 tons capacity, using partially burnt town gas
- 4 continuous bright-annealing furnaces for stainless steels, the atmosphere being cracked ammonia.

SPECIAL TYPES OF MILL

Some comments on three special types are given below, all three being fairly recent designs. Apart from these three, the use of pre-loaded stands, as described by Leufvén,[2] is of great interest.

The Driven Backing Roll 4-High Mill[3,4]

This type of 4-high reversing mill is designed to make use of small-diameter work rolls, with their advantages for rolling thin and hard material, by removing the limitation on roll diameter when the work rolls are driven. An earlier method of doing this was to have no drive to any roll, as in the Steckel mill. Heavier reduction than the Steckel mill is capable of, with less tendency to strip breakage, is achieved by driving the backing rolls. A further advantage is that lateral bending of the work rolls, which is one of the limitations of the Steckel, especially on heavier gauges, is reduced because the backing rolls tend to drive the work rolls backwards in partial compensation for the effect of heavy front tension.

A number of these mills have now been built, and so far as is known no difficulties with roll skidding have been experienced. These mills use a considerable amount of tension, the ratio of coiler motor power to main motor power going up much higher than in a conventional 4-high. For example the original C.M.P. mill, 3 in. × 14 in. × 10 in., has 100 h.p. on the rolls and 50 h.p. on each coiler. A second C.M.P. mill of the same width, 3 in. × 15 in. × 10 in., has 200 h.p. on the rolls and 150 h.p. on each coiler. Being designed for a wide range of strip sizes the latter mill has two motors to each coiler to double the tension range. Another design of mill with driven backing rolls, known as the 'Package' mill, has this ratio similar to a conventional 4-high.

When driving the backing rolls it is convenient to dispense with the usual pinions and to drive each roll individually, using two motors. This has the incidental advantage of avoiding the need for accurate matching of roll diameters.

Like the Steckel mill, the C.M.P. design employs two internally water-cooled pass-line rollers to help cool the strip. Rolling can be with mineral or soluble oil.

The absence of drive to the work rolls offers some reduction in roll-changing time. It also makes the use of tungsten carbide rolls a practical proposition; they are in regular use on this type of mill.

This type of mill is very suitable for rolling thin strip, combining medium heavy reductions with rolling speeds as high as 1400 ft./min. on narrow thin mild steel. Its characteristics lie between those of an ordinary 4-high mill and a Sendzimir mill. Gauge variation and strip shape are very satisfactory.

The 'Y' Mill (Fig. 12*a*)

This reversing mill, with a name derived from the arrangement of the rolls in the form of a letter 'Y,' uses work rolls of different diameters with an effective roll diameter equal to the harmonic mean of the two actual diameters. This effective diameter is that which would give the same length of arc of

contact, for the same reduction, as the two different diameters, assuming no roll flattening. The smaller work roll is supported both vertically and laterally by a multi-cluster arrangement, and the other work roll is large enough to need no lateral support. It combines an effective diameter less than in a normal 4-high mill with the ease of adjustment of a 4-high. This diameter is not greatly different from that used in a driven-backing-roll 4-high mill.

The roll diameters of a 20-in. mill for rolling 16-in. strip, as commissioned in France in 1952, are:

Upper work roll	3 in.
Lower work roll Intermediate rolls	6 in.
Cluster backing rolls	17¾ in.
Bottom backing roll	19½ in.

(Effective work-roll diameter 4 in.)

Roll adjustment is by motor-driven screws beneath the bottom roll. A 600-h.p. motor drives the bottom work roll and the two intermediate rolls. Each coiler has a 200-h.p. motor. Maximum speed is 1200 ft./min.

The three driven rolls must be of the same diameter; of these the bottom work roll wears far more rapidly. To avoid unnecessary grinding of the intermediate rolls the recommended practice is to keep a set of nine rolls of the same diameter, so that seven work rolls can be used with one pair of intermediates.

The Sendzimir Mill (Fig. 12*b*)

This is a multi-cluster reversing mill designed to make use of the smallest practical diameter of work roll in order to achieve the greatest possible reduction between anneals, and to give very good accuracy in gauge. Depending on the size of the mill, there are either one or two sets of intermediate rolls to obtain sufficient rigidity of support. Drive is to four intermediate rolls; on mills with two sets of intermediates the drive is to the second (i.e. outermost) intermediate rolls.

A distinguishing feature of the design is that instead of backing rolls supported by their necks it uses a number of roller-bearings mounted on stationary shafts. These shafts are supported between the roller-bearings by saddles which distribute the load over the width of the housing. Unlike ordinary mills, the housing is in one piece in the form of a box with a wide window at the sides for access to the rolls and small slots in the ends for the passage of the strip. On the larger mills external means of adjusting the saddles for the internal top shafts are provided, to give the effect of a change of roll camber. Some operators do not use this adjustment.

Instead of a conventional screwdown, the shafts which carry the backing roller-bearings are mounted eccentrically and are rotated by a rack and pinion arrangement to adjust the work-roll setting. With this system there is no adjusting one end of the rolls relative to the other.

Provision is made, however, for control of strip edges, by adjustiug the first intermediate rolls axially. The ends of these rolls are tapered to a degree and length determined by experience. The first intermediates, however, can usually be adjusted axially.

A mineral oil is used for rolling and bearing lubricant. Although a copious flood of oil is used, rolling speeds are generally low, mostly 200–400 ft./min., because of cooling problems. Soluble oil is reported to be used on one mill rolling mild-steel strip.

Work-roll changing is very rapid, taking 1 or 2 min., so little delay is involved in changing rolls before the final pass. Before grinding they are often stress-relieved.

The mill is made in a number of sizes and in the mill designation, such as ZR 24–14, the first number denotes the mill type (i.e. roll arrangement and diameter) and the second number gives the maximum strip width. Some types such as the ZR 15 and 16, with nominally $\frac{15}{32}$-in. and $\frac{5}{6}\frac{5}{4}$-in. dia. work rolls, have one set of intermediate rolls in a 1 : 2 : 3 formation. In these two mills, the backing bearings are interlaced so that they can be of relatively large diameter. The larger mills, ranging up to the ZR 22 with $2\frac{1}{8}$-in. nominal work-roll diameter, employ the 1 : 2 : 3 : 4 arrangement. This is also used in the smallest mill so far reported, the ZR 32–4, which has $\frac{1}{4}$-in. work rolls, two sets of intermediate rolls, and $1\frac{7}{8}$-in. dia. bearings.

In connection with remarks on the cluster mill, the ratio of the diameters of the first intermediate rolls and the work rolls in this series of mills is in the region of 2 : 1, with the lines of centres at 45° to the vertical. No side guides are used on these mills; on certain small mills endwise adjustment is provided on the coilers to help keep the strip straight.

A feature of the mill is the high tension used. Each coiler has motors rated usually at between half and three-quarters of the power of the main motor. Accurate tension control is required, and on the smaller mills this is obtained by using regulating tensiometers.

Sendzimir mills are in use on practically all qualities of strip. Economically their heavy reductions between anneals using a few slow passes must be weighed against the possible alternatives of higher speed, more passes, and more intermediate anneals according to the product required to be rolled.

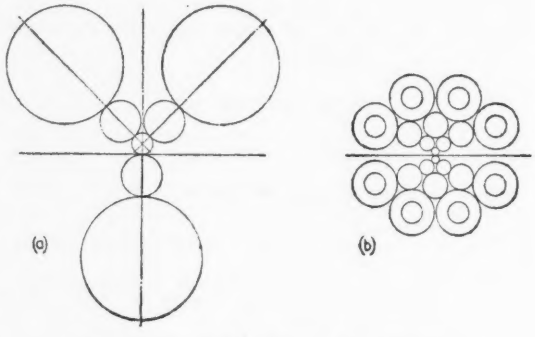

Fig. 12—(*a*) Y mill ; (*b*) Sendzimir mill

The strip rolled on a Sendzimir mill has a high degree of gauge accuracy, with little edge droop but, judging from observations on several mills, it sometimes shows signs of ripple. This is generally improved by subsequent annealing, and a large amount of stainless steel is now produced by using a Sendzimir mill for quick reduction, softening, descaling, and then skin passing for shape and surface finish on a large 2-high mill.

AUTOMATIC GAUGE CONTROL

General

The problem of obtaining uniformity of gauge along the length of a coil of strip has become important as rolling speeds have increased. On old mills running at 80 ft./min. the operator had plenty of time to correct for any changes, but at speeds used in many modern mills this is no longer effective. Consequently, attempts have been made in recent years to develop means of correcting automatically for changes in gauge.

The main causes of these variations are:

(i) Variation in thickness of the hot-rolled strip
(ii) Variation in gauge with the speed of cold-rolling, which produces thicker strip when the speed is low, mainly at the ends of a coil. This speed effect is generally attributed to change of coefficient of friction in the roll gap with change of speed
(iii) Miscellaneous causes, such as non-uniformity of hardness, eccentricity of rolls and bearings, variation in tension, etc.

Methods of control may be grouped according to the means of obtaining an indication of gauge error and the means of applying the correction. An error signal can be obtained from:

(i) A flying micrometer on the delivery side of the mill
(ii) A flying micrometer on the entry side of the mill
(iii) The mill itself.

If the delivery side micrometer is used the system is fully automatic and will correct in principle for any factor which causes a variation in gauge of the strip passing through the micrometer. The inherent disadvantage is that the gauge error is measured on strip which has already left the rolls, so that the equipment tends to be unstable and may break into oscillation. This can be explained in simple terms by considering a strip which is uniform except for one short thick portion. When this reaches the micrometer the control acts on the rolls and causes a thin spot in strip which would otherwise be on gauge. This thin spot travels to the micrometer and the effect is repeated. The system can be used if it is adjusted to be relatively sluggish in operation.

The alternative of controlling from the entry-side micrometer avoids instability problems, but at first sight appears unattractive. In this position the micrometer is sensitive to changes in gauge of the ingoing strip and to nothing else, so that there is no correction for any other cause of gauge variation. Furthermore, the system is not fully automatic, as it has no means of monitoring the outgoing gauge; to overcome this the operator can have ingoing and outgoing gauge variation displayed side by side.

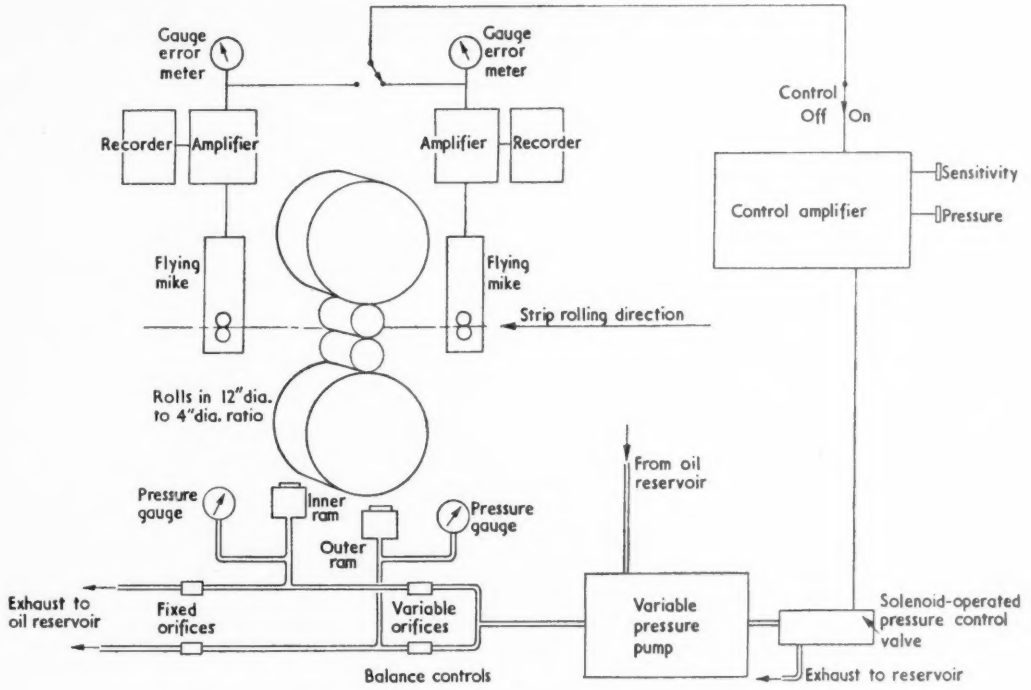

Fig. 13—Diagram of automatic gauge control system

He can then adjust the sensitivity control to the optimum setting.

The advantage of the third method, which is due to B.I.S.R.A.,[5–8] is that it eliminates delays due to the spacing between rolls and flying micrometer. The gauge error is measured at the same instant as it is desired to apply the correction, irrespective of the speed of the strip.

This system corrects for speed effect, variation of ingoing gauge, and hardness, though a means of overcoming drift due to thermal expansion of the rolls appears to be necessary. The correction is applied either by varying the strip tension or by adjusting the roll setting; the latter can be done hydraulically or by the screwdown motors. These promising methods are still in the development stage.

Recent developments include mills which are mechanically very stiff, and automatic gauge control which has the effect of making an ordinary mill equivalent to an extremely stiff mill.

Gauge Control from Flying Micrometer (Fig. 13)

A control system using a flying micrometer has been developed and used on full production at Stocksbridge for over a year. It is fitted on one of the 4 in. × 12 in. × 7½ in. reversing mills, and is arranged so that by means of a switch either of the two flying micrometers can be used to supply the error signal and thus to control the setting of the rolls.

The mill to which gauge control is fitted has hydraulic adjustment of the bottom roll instead of the conventional screwdown. Oil pressure to the two hydraulic rams is obtained from a single pump, the delivery pressure of which is varied by a solenoid-controlled valve. The design is such that, except at pressures lower than those used in rolling, an almost linear relationship is obtained between the direct current flowing through the solenoid and the delivery pressure of the pump.

The solenoid current is obtained from an amplifier and is variable by the 'pressure' control which sets the operating pressure of the mill. This control is adjusted to give the required outgoing gauge. When gauge control is required, a switch is operated which adds to the steady solenoid current a fraction of the amplified error signal from the flying micrometer on the entry side. The proportion of the error signal used is set by the 'sensitivity' control, graduated in lb./sq. in. per 0·0001 in. gauge error.

Ingoing and outgoing gauge variations are displayed side by side on two meters, and at the moment on two pen recorders. The operator adjusts the sensitivity control so that a variation of ingoing gauge is neither under- nor over-corrected. In practice the settings for particular passes become known and can be made at the onset. For the class of work normally performed on this mill the settings are such as to give between 7500 and 10,000 lb. change of load for an ingoing gauge error of 0·0001 in.

An important feature is the necessity to be able to control the strip shape by varying the load on one ram relative to the other, equivalent to adjusting each screw individually on a conventional mill. This is achieved by having two variable orifices each dropping the pressure to one ram by up to about 15% below the pump delivery pressure. The pressure change for gauge correction is reduced by the same proportion as the steady pressure when a levelling or a 'balance' control is adjusted; the micrometer reads gauge in the centre of the strip. The good results obtained show that in practice the main cause of gauge error in the strip (usually 0·010 in. and thinner in this mill) lies in irregularity of gauge in the ingoing material. Figure 11 shows simultaneous records of ingoing and outgoing gauge during a controlled pass.

Ironing out gauge variation, however, introduces variation of hardness, so that the control is used on the last pass before annealing. To give improved correction, such as for under- or over-correction, two controlled passes are usually given. Generally the strip has a 4-pass schedule on this mill, and correction is applied on the second and fourth passes. On the third pass the mill is effectively a constant-pressure mill, and hardness variation arising in the second pass gives rise to corresponding, but much reduced, gauge variation in the third pass. This is removed in the fourth pass.

Although it does not correct for speed effect on the pass being controlled, the system does operate on gauge variation due to speed effect in previous passes, so that an overall improvement is made.

If the 'direction' switch is set to obtain the error signal from the flying micrometer on the outgoing side, and the sensitivity control is left in the position required for using the ingoing-side micrometer, the equipment is unstable and breaks into oscillation. It can be used if the sensitivity is somewhat reduced, resulting in slight under-correction.

The equipment is relatively simple, has run for over a year with only minor breakdowns, and, despite the limitations already pointed out, has proved very effective. In the author's opinion automatic gauge control will develop until it becomes a generally accepted method of producing strip to close tolerances. It should find its place not only in cold-rolling mills, but also in mills producing hot-rolled strip.

Acknowledgments

The author wishes to thank the directors of Samuel Fox and Co. Ltd., for permission to publish this paper. He would also like to pay tribute to the many people, both in the office and on the shop floor, without whose combined efforts in building up the cold-rolling department this paper would not have been written.

References

1. R. B. Sims: *J. Iron Steel Inst.*, 1954, vol. 178. pp. 19–34.
2. A. Leufvén: *Ibid.*, 1954, vol. 176, pp. 415–423.
3. L. L. Wilson: *Iron Steel Eng.*, 1949, Nov., pp. 71–75.
4. M. D. Stone: *Ibid.*, 1953, Feb., pp. 61–74.
5. W. C. F. Hessenberg and R. B. Sims: *Proc. Inst. Mech. Eng.*, 1952, vol. 168, ser. A, pp. 75–81.
6. R. B. Sims, J. A. Place, and P. R. A. Briggs: *J. Iron Steel Inst.*, 1953, vol. 173, pp. 343–360.
7. R. B. Sims: *Engineering*, 1953, vol. 175, p. 33.
8. R. B. Sims and P. R. A. Briggs: *Sheet Metal Ind.*, 1954, vol. 31, pp. 181–190, 203.
9. R. B. Sims and K. H. Slack: *Inst. Mech. Eng.*, Advance Copy for meeting on 3rd Dec., 1954.

JOINT METALLURGICAL SOCIETIES' MEETING IN EUROPE

Co-Chairmen of American Committee

James B. Austin

Leo F. Reinartz

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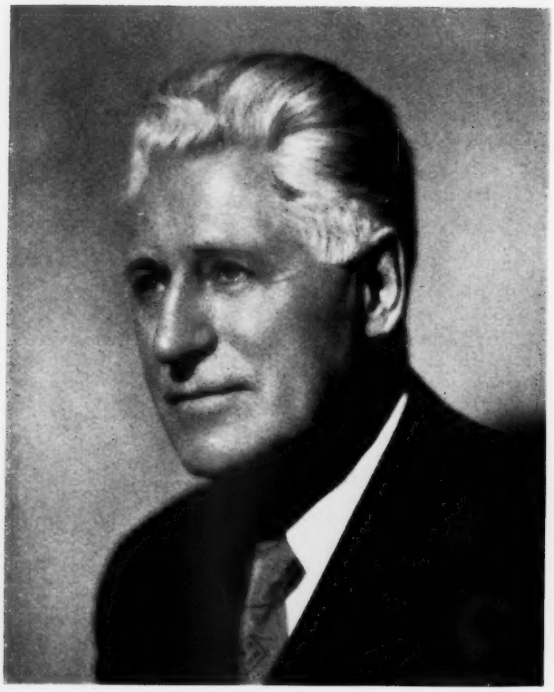
American Institute of Mining and Metallurgical Engineers



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H. DeWitt Smith

Secretary:
Ernest O. Kirkendall

American Society for Metals

President:
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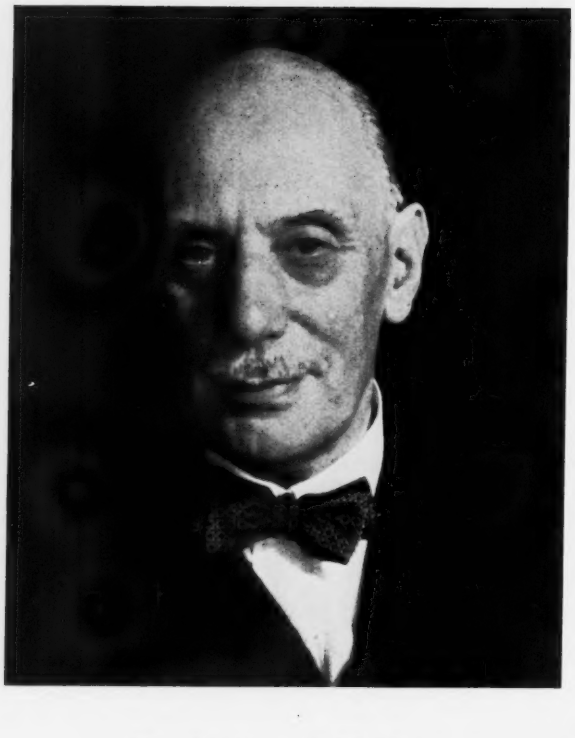

The Iron and Steel Institute

President:
Sir Charles Bruce-Gardner, Bt.

The Institute of Metals

President:
Dr. Maurice Cook

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JOINT METALLURGICAL SOCIETIES' MEETING IN EUROPE, 1955

Great Britain · Germany · Belgium · France · Sweden

INTRODUCTION

The American Institute of Mining and Metallurgical Engineers and the American Society for Metals have accepted invitations from The Iron and Steel Institute and The Institute of Metals and from the leading metallurgical societies in Belgium, France, Germany, and Sweden to send representatives to a Joint Metallurgical Societies' Meeting in Europe.

His Royal Highness The Duke of Edinburgh, K.G., has graciously consented to be Patron of the Meeting in Great Britain.

The dates of the meeting are 1st to 7th June in Great Britain, 9th to 12th June in Düsseldorf (Germany), 13th June at Liège (Belgium), and 14th to 18th June in France.

The objects of this meeting are to establish personal contacts between experts in the U.S.A. and Canada and in Europe, to provide opportunities for scientific and technical discussion, to enable visitors from the U.S.A. and Canada to see something of the metallurgical industries of Europe, and to foster better understanding and co-operation among all concerned.

The scope of the meeting will cover ironmaking (including coke and ore preparation); steelmaking; mechanical working and heat-treatment, both ferrous and non-ferrous (including hot and cold rolling, forging, wire drawing, and continuous casting, but not the foundry industry); refining and fabrication of non-ferrous metals; heat-treatment; surface treatment (including finishing and coating); metallurgical education and training in industry; research. Most of the technical and scientific work will be conducted by means of discussion groups. Group leaders who are recognized authorities will guide the discussion on each subject and ensure that leading experts take part.

Participation by Members of the Institute

The technical visits in and near London, the tours to industrial districts in Great Britain, the sections of the meeting in Germany, Belgium, and France, and the post-meeting tours in Europe have been arranged primarily for the American visitors to Europe. Participation will therefore be by personal invitation only. Relatively few members of The Iron and Steel Institute and The Institute of Metals can be invited to take part in these sections of the meeting.

PROGRAMME OF THE MEETING

Part I—Programme in Great Britain

Section A: Items Available to Members of the Institute

Wednesday, 1st June

Morning: Registration at Church House, Westminster, London, S.W.1.
Tour No. 1—Sightseeing in London.

Afternoon: Opening Plenary Session at Church House. Speeches of welcome by the Presidents of The Iron and Steel Institute and The Institute of Metals, with replies by the Presidents of the American Institute of Mining and Metallurgical Engineers and the American Society for Metals, or their deputies. Presentation of the Bessemer Gold Medal for 1955 to Professor John Chipman (M.I.T.). Nominations to Honorary Membership of the Institute. Other awards. Inaugural Lecture on "*X-Ray Analysis and the Structure of Metals*" by Sir Lawrence Bragg, O.B.E., M.C., F.R.S.

Evening: Reception at Lancaster House by invitation of Her Majesty's Government. Guests will be received by the Minister of Supply, the Rt. Hon. Reginald Maudling, C.H., M.P. (By personal invitation only.)

Thursday, 2nd June

All Day: Meetings of six simultaneous Technical Discussion Groups at Church House and elsewhere (for details *see* p. 203).

Evening: Banquet at the Guildhall by invitation of the British Iron and Steel Federation. (By personal invitation only.)

Friday, 3rd June

Morning: Meetings of six simultaneous Technical Discussion Groups at Church House and elsewhere (for details *see* p. 203).

Afternoon: *Tour No.* 6—Sightseeing in London, or *Tour No.* 10—Kenwood House, Hampstead.

Saturday, 4th June

Tour No. 11 (all day)—Oxford Colleges and Laboratories

or

Tour No. 12 (afternoon)—Gardens of the Royal Horticultural Society at Wisley, Surrey.

Sunday, 5th June

Tour No. 14. (all day)—Hampton Court Palace ; lunch at Great Fosters ; Windsor Castle ; Eton College.

or

Tour No. 15 (afternoon)—Surrey Downs, Newlands Corner, Albury House, Dorking, and Boxhill.

Monday, 6th June

Afternoon : *Tour No.* 20—Hatfield House and Luton Hoo.

Tuesday, 7th June

All day : *Tour No.* 21—Cambridge Colleges and Laboratories.

Several special sightseeing tours for the ladies will be arranged on these days, including visits to Hampton Court, Kew Gardens, Winchester, and Canterbury.

Section B : Technical Visits in or near London

(*Membership restricted*)

Friday, 3rd June

Afternoon : Choice of *one* of the following :

Tour No. 7—National Physical Laboratory (Metallurgy Division), Teddington.

Tour No. 8—British Iron and Steel Research Association Laboratories, Battersea.

Tour No. 9—British Non-Ferrous Metals Research Association, Euston.

Monday, 6th June

All Day : Choice of *one* of the following :

Tour No. 16—Stewarts and Lloyds Ltd., Corby.

Tour No. 17—Enfield Rolling Mills Ltd.

Tour No. 18—A.P.V. Co., Ltd., Crawley.

Tuesday, 7th June

Afternoon : Choice of *one* of the following :

Tour No. 22 — National Physical Laboratory (Metallurgy Division), Teddington (as *Tour No.* 7).

Tour No. 23—British Iron and Steel Research Association Laboratories, Battersea (as *Tour No.* 8).

Tour No. 24— British Non-Ferrous Metals Research Association, Euston (as *Tour No.* 9).

Section C : Tours to Metallurgical Areas in Great Britain

(*Membership very limited*)

Tour U.K. 1 : SOUTH WALES

Saturday, 4th June—By bus to Stratford-on-Avon, with visit to the Shakespeare Memorial Theatre.

Sunday, 5th June—By bus from Stratford-on-Avon *via* Gloucester to Porthcawl.

Monday, 6th June—Visit to the Margam and Abbey Works of the Steel Company of Wales Ltd.

Tuesday, 7th June—Visit to *one* of the following :

Trostre Works of the Steel Company of Wales Ltd.

Clydach Works of the Mond Nickel Co., Ltd.

Guest Keen Iron and Steel Co., Ltd., Cardiff, and Guest Keen and Nettlefolds (South Wales) Ltd., Cardiff.

Rogerstone Works of the Northern Aluminium Co., Ltd.

(Ladies and Gentlemen will return to London by train in the evening.)

Tour U.K. 2 : BIRMINGHAM

Saturday, 4th June—by Bus to Stratford-on-Avon, with visit to the Shakespeare Memorial Theatre.

Sunday, 5th June—Sightseeing bus tour : Cotswolds, Broadway, etc.

Monday, 6th June—Visit to the Witton Works of Imperial Chemical Industries Ltd. (Metals Division).

Tuesday, 7th June: *Morning*—Visit to *either* James Booth and Co., Ltd., *or* Henry Wiggin and Co., Ltd. *Afternoon*—Visit to *either* Birmingham Aluminium Castings (1903) Ltd., *or* the Department of Metallurgy, Birmingham University.

(Ladies and Gentlemen will return to London by train in the evening.)

Tour U.K. 3 : SHEFFIELD and SCUNTHORPE

Sunday, 5th June—By train to Sheffield.

Monday, 6th June—*Morning*—Visit to *either* Thos. Firth and John Brown Ltd. *or* The British Iron and Steel Research Association, Sheffield Laboratories. *Afternoon*—Visit to *either* The English Steel Corporation Ltd. *or* The United Steel Companies Ltd., Swinden Laboratories.

Tuesday, 7th June—*Either* all-day visit to Appleby-Frodingham Steel Co., Scunthorpe,

or

Morning—Visit to Hadfields Ltd.

Afternoon—Visit to *either* William Jessop and Sons Ltd., *or* Shepcot Lane Rolling Mills Ltd.

(Ladies and Gentlemen will return to London by train in the evening.)

Tour U.K. 4 : DURHAM and YORKSHIRE

Sunday, 5th June—By train to Durham ; sightseeing.

Monday, 6th June—Visit to Consett Iron Co., Ltd.

Tuesday, 7th June: *Morning*—Visit to Cleveland and Lackenby Works of Dorman, Long and Co., Ltd. *Afternoon*—Visit to the Wilton Park Factory Estate of Imperial Chemical Industries Ltd.

(Ladies and Gentlemen will return to London by train the same evening.)

Tour U.K. 5 : SCOTLAND

Friday, 3rd June—Leave London by sleeping-car train.

Saturday, 4th June: *Morning*—Free in Edinburgh. *Afternoon*—Sightseeing, including Edinburgh Castle and Holyrood House.

Sunday, 5th June—By bus to Glasgow *via* Forth Bridge, Stirling, Callendar, and the Trossachs.

Monday, 6th June: *Morning*—Visit to Clyde Iron Works and Clyde Bridge Steelworks of Colvilles Ltd. *Afternoon*—Visit to *either* British Aluminium Co., Ltd., Falkirk, *or* William Beardmore and Co., Ltd.

Tuesday, 7th June—Excursion by steamboat on the Clyde for visit to the shipyards of John Brown and Co. (Clydebank), Ltd., thence by bus to Helensburgh, Gareloch, Loch Long, and Loch Lomond.

(Ladies and Gentlemen will return to London by sleeping-car train, leaving Glasgow in the evening and arriving in London on the morning of Wednesday, 8th June.)

On each of these tours there will be several special sightseeing excursions for the ladies, as well as a number of social functions.

Part II—Programme in Europe

(Membership strictly limited)

Section A : GERMANY

The Meeting in Germany will be held by invitation of Verein Deutscher Eisenhüttenleute and Deutsche Gesellschaft für Metallkunde. Bundespräsident Dr. T. Heuss has kindly agreed to be Patron.

8th June—By train or air from London to Düsseldorf.

9th June : *Morning*—Plenary Opening Session in Düsseldorf.
Afternoon—Technical Discussions in Düsseldorf.
Evening—Reception by the Lord Mayor of Düsseldorf.

10th June—Visits to iron and steelworks and laboratories in Ruhr district.

11th June: *Morning*—Technical Discussions in Düsseldorf.
Afternoon—Free in Düsseldorf.

12th June—Excursion by steamship on the Rhine.
13th June—Ladies and Gentlemen will leave Düsseldorf by air or by train.

Section B : VISIT TO LIÈGE and Travel to Paris.

13th June—A visit to Liège has been arranged *en route* from Düsseldorf to Paris, by invitation of the Centre National de Recherches Métallurgiques. Visitors will be entertained to lunch. They will then divide into groups for visits to works and laboratories and for technical discussions. After a Reception they will continue the journey to Paris by special train. Those who prefer may travel direct from Düsseldorf to Paris by train or by air.

Section C : FRANCE

The Meeting in France is being held by invitation of the Société Française de Métallurgie.

14th June (in Paris)—Opening Plenary Session at the Sorbonne. Meetings of Discussion Groups. Technical visits and sightseeing. Official reception at the Hotel de Ville. Evening reception at the Louvre.

15th June (in Paris)—Meetings of Discussion Groups. Technical visits and sightseeing.

16th and 17th June—Tours to industrial districts will include :

Tour F6: Northern France (Lille—Denain).
Tour F7: Northern France (Douai and Le Havre).
Tour F8: Eastern France (Metz—Lorraine).
Tour F9: Central France (St. Étienne—Le Creusot).
Tour F10: South Eastern France (Clermont-Ferrand, Issoire, Aix-les-Bains, St. Jean-de-Maurienne).

(Alternatives to the above include a two-day excursion to the Châteaux de la Loire (*Tour F13*), and day visits to ferrous and non-ferrous works and to laboratories near Paris.

18th June (in Paris)—Visit to the Institut de Recherches de la Sidérurgie at St. Germaine-en-Laye. Official reception and banquet at Versailles.

Section D : POST-MEETING TOURS

After the Main Meeting, tours are being arranged to other European countries, including Austria (by invitation of the Eisenhütte Oesterreich), Italy (by invitation of the Associazione Italiana di Metallurgia), Spain (by invitation of the Instituto del Hierro y del Acero), and Switzerland. Visitors will also be made welcome in Sweden by Jernkontoret, before and after the main meeting.

TECHNICAL SESSIONS

The following subjects have been selected for discussion at the Technical Sessions to be held in London on 2nd and 3rd June. The subjects included in each Session will be discussed simultaneously in separate Groups. The names of the Group Leaders are given in parentheses.

SESSION I

Thursday, 2nd June, Morning

A. Blast-Furnace Practice : Ore Preparation and Beneficiation, including Agglomerating, Sintering, and the Use of the Resultant Materials in the Blast-Furnace Burden. (Mr. G. D. Elliot, Appleby-Frodingham Steel Co.)

B. Steelmaking : Basic Open-Hearth Furnace Design and Operation, with Special Reference to Port Design, Flow Lines, Flame Radiation, the Proper Use of Instruments, etc. (Mr. W. C. Bell, Stewarts and Lloyds Ltd.)

C. Melting and Casting Techniques in the Non-Ferrous Metals Industries, with Particular Reference to Recent Developments in the Production of High-Quality Ingots for Subsequent Working. (Dr. W. O. Alexander, I.C.I. Ltd., Metals Division.)

D. Continuous Casting, Including the Continuous and Direct Casting of Aluminium and Aluminium Alloy Shapes for Subsequent Working ; Continuous Casting of Copper and Copper Alloys ; Continuous Casting of Carbon and Alloy Steels. (Mr. A. W. Baker, British Non-Ferrous Metals Research Association, and Mr. J. Savage, British Iron and Steel Research Association.)

E. High-Temperature Alloys : Recent Developments in their Manufacture, Use, and Properties, including Resistance to Creep and Scaling. (Dr. L. B. Pfeil, Mond Nickel Co., Ltd.)

F. (i) Education and Training of a Metallurgist ; (ii) Education and Training of Those Engaged in Industry. (W. D. Pugh, English Steel Corporation Ltd.)

SESSION II

Thursday, 2nd June, Afternoon

G. Iron and Steelmaking. Desulphurizing and Desiliconizing—Various Methods. (Mr. R. A. Hacking, Richard Thomas and Baldwins Ltd.)

H. Steelmaking : The Place of the Electric Arc Furnace in Tonnage Steel Manufacture. (Mr. G. Tinker, Birlec Ltd.)

I. Production of Steel Strip and Sheet, with Particular Reference to Materials Suitable for Pressing. (Mr. H. Edwards, John Summers and Sons, Ltd.)

J. Problems of High-Speed Wire Drawing of Ferrous and Non-Ferrous Metals. (Mr. R. S. Brown, Rylands Bros., Ltd.)

K. Rate Processes in Metallurgy—Nucleation and Growth, Diffusion, Transformation, etc. (Dr. D. McLean, National Physical Laboratory.)

KK. Practical Aspects of the Heat-Treatment of Special Alloys, including Equipment and Methods of Control. (Dr. Ivor Jenkins, General Electric Co., Ltd.)

SESSION III

Friday, 3rd June, Morning

L. Latest Developments and Future Trends in the Study of the Physical Chemistry of Steelmaking. (Dr. J. Pearson, British Iron and Steel Research Association.)

M. Production of Steel Ingots of High Quality by Processes other than Continuous Casting. (Mr. N. H. Bacon, Steel Peech and Tozer, Ltd.)

N. Production of Metals of High Purity, including Vacuum Melting and Zone Melting and other New Techniques. (Dr. J. C. Chaston, Johnson, Matthey and Co., Ltd.)

O. Extrusion of Ferrous and Non-Ferrous Metals, including the Use of Lubricants. (Dr. J. W. Jenkin, Tube Investments Ltd.

P. Fracture of Metals under Static or Dynamic Loads. (Dr. N. P. Allen, National Physical Laboratory.)

PP. Heat-Treatment of Forgings. (Dr. H. H. Burton, English Steel Corporation Ltd.)

AMERICAN AND BRITISH PARTICIPATING SOCIETIES

AMERICAN INSTITUTE OF MINING AND METALLURGICAL ENGINEERS

The American Institute of Mining and Metallurgical Engineers was first organized in 1871, with a membership of 71. Now, with a total membership of over 16,000, it has 39 Local Sections throughout practically the entire United States, and in Canada, Brazil, and the Philippine Islands. Although the Institute had, from its inception, been concerned with both mining and metallurgical activities, the words, "and Metallurgical" were not introduced into its title until 1919.

The first forty years of the Institute's existence were devoted mainly to organization and foundation, but during this time it was already becoming well-known in America. It took part in the Centennial Exposition held in Philadelphia in 1876, and in 1893 played a prominent part in the World's Columbian Exposition in Chicago and in the organization of the mining and metallurgical departments of the World Engineering Congress held in conjunction with the Exposition. Another important step was taken in 1904, when the Institute, together with the American Society of Mechanical Engineers and the American Institute of Electrical Engineers, established the United Engineering Society (now known as the United Engineering Trustees), and, by means of a generous donation from the late Andrew Carnegie, the Society was able to build the Engineering Societies Building at 29 West 39th Street, New York, which has since been the permanent headquarters of the Institute. The three Societies, together with the American Society of Chemical Engineers which joined at a later date, inaugurated the Engineers Joint Council, and each partly endows the Engineering Societies Library.

The formation of Professional Divisions of the A.I.M.E. began in 1918, when the American Institute of Metals was absorbed by the A.I.M.E. as the Institute of Metals Division. Today there are ten Divisions, each of which is self-governing under the Board of Directors of the Institute: Coal; Industrial Minerals; Minerals Beneficiation; Mining, Geology, and Geophysics; Extractive Metallurgy; Institute of Metals; Iron and Steel; Petroleum; Mineral Economics; Mineral Industry Education. The first four of these Divisions have been grouped into the Mining Branch, the next three into the Metals Branch, and the Petroleum Division forms the Petroleum Branch; each of these Branches has its own monthly publication, viz.: *Mining Engineering*, *Journal of Metals*, and *Journal of Petroleum Technology*. The last two Divisions are all-Institute ones.

Apart from the above publications, the A.I.M.E. issues its own *Transactions*; as early as 1908 it was awarded a gold medal at the Jamestown Ter-Centennial Exposition in recognition of the high quality of its publications. In 1909 the publication of a monthly *Bulletin* was undertaken; ten years later the *Bulletin* was succeeded by *Mining and Metallurgy*, also published monthly. Since 1934 the Institute has also published *Metals Technology*, which appears twice quarterly. In addition it undertakes the production of Technical Publications and various special volumes.

Some of the better known of the medals endowed by the A.I.M.E. include the Charles F. Rand Memorial Medal, the James Douglas Gold Medal, the William Lawrence Saunders Medal, and the Anthony F. Lucas Medal. The Howe Memorial Lecture, which is held under the auspices of the Institute, commemorates a Past-President, and, since its inception in 1923, has been delivered by a number of British, Swedish, and German scientists, as well as those from the U.S.A.

The Institute played an important role during both World Wars. In World War I it was represented on the American Engineering Council, the Naval Consulting Board, and other organizations, and co-operated with the U.S. Bureau of Mines. During the Second World War it was represented on many organizations, and gave assistance on numerous problems to the War, Navy, and State Departments.

The Institute also incorporates a Women's Auxiliary, whose responsibilities include social events at meetings, the organization of libraries in industrial areas, hospitals, etc., and welfare in general.

AMERICAN SOCIETY FOR METALS

The American Society for Metals, which was established in 1913 in Detroit, is devoted exclusively to all phases of the metal industry, and is the largest group of metal engineers in the world. Its original membership of 12 has now grown to over 22,000, 60% of which is employed in the field of metal fabrication, 25% in plants producing ferrous and non-ferrous metals, and 15% in education and research.

Among the most important of the many functions of the Society is the publication of books and journals for the metals industry. These include the *Metals Handbook*, the monthly *Metal Progress*, the *Metals Review* which is combined with the Review of the Metal Literature, prepared by the Battelle Memorial Institute, and the *Transactions* of the Society. In addition it also prepares data sheets in booklet form, which are distributed free to the metallurgical departments of colleges and universities, and films pertaining to the metals industry.

Another function of the Society is the operation of an employment service for members and for the industry; it has also inaugurated a summer employment bureau available to students, whether members or not, at engineering schools in the U.S.A. and Canada.

The Society is active in the organization and operation of national meetings. It owns and operates the National Metal Exposition, which is held annually, and which incorporates a metallographic exhibit presented by the Society, and the biennial Western Metal Exposition, serving metal engineers in the eleven Western States. The National Metal Congress, and the Western Metal Congress are also sponsored by the Society, which was also the sponsor of the first World Metallurgical Congress held in Detroit in 1951, and attended by delegates from 39 countries.

An active liaison between the Society and the Defense Department of the U.S. Government has been established, and at the request of the Metallurgical Advisory Board the Society acts in an advisory capacity to the Defense Department by appointing committees to prepare reports and suggestions on assigned problems. The Metallurgical Advisory Board has also officially designated the Society as the medium through which information relative to metallurgical problems may be transmitted to the profession.

In the field of education and research, the Society also plays an important part. Through the National Science Teachers' Association, it sponsors the Annual Science Achievement Award with the aim of creating a student interest in science and the advantages and merits of engineering as a career, and also sponsors awards for science teachers. The Society was also responsible for the inception of the Annual A.S.M. Teaching Award in Metallurgy, which is open to teachers of metallurgy in the U.S.A. and in Canada. Other achievements of the Society include the American Society for Metals Foundation for Education and Research which has an initial grant of $650,000, and the A.S.M. Visiting Lectureship.

The local membership of the Society is divided into 82 chapters, which hold over 500 monthly meetings each year. The majority of these chapters organize evening educational courses which are supported by a grant from the Society and which attract an attendance of over 16,000 yearly.

The national offices of the American Society for Metals are at 7303 Euclid Avenue, Cleveland 3, Ohio.

THE IRON AND STEEL INSTITUTE

The Iron and Steel Institute was founded on 25th February, 1869, on the initiative of a group of ironmasters in the North of England, with the following objects : To afford a means of communication between members of the iron and steel industries ; and to arrange periodical meetings for the purpose of discussing practical and scientific subjects bearing on the manufacture and working of iron and steel.

Thirty years after its formation, the Institute was incorporated by Royal Charter, and in 1908 it was granted the right to bear arms ; the Coat of Arms incorporates the heraldic devices of the first President, the seventh Duke of Devonshire, and a later President, Sir Isaac Lowthian Bell, Bt., F.R.S. The Institute has enjoyed the honour of Royal Patronage since 1902, when H.M. King Edward VII became Patron ; in July, 1952, H. M. Queen Elizabeth II was graciously pleased to confer Her Patronage upon the Institute.

For the first four years, the offices of The Iron and Steel Institute were situated in Middlesbrough, and in 1873 they were transferred to London. By means of assistance from the iron and steel and associated industries, the Institute moved into its present premises at 4 Grosvenor Gardens, London, S.W.1, in 1938.

One of the major functions of the Institute is the organization of meetings for the presentation and discussion of technical and scientific papers, and visits to iron and steel and engineering works are often included in the programmes of these meetings. Apart from the Annual General and Autumn Meetings, Special Meetings are held from time to time in the U.K. and abroad. In recent years, such meetings have been held in Austria (1951), the Netherlands (1953), and Sweden (1954). In addition, the Institute, in co-operation with other Societies, often arranges to hold Special Meetings or Symposia for the discussion of particular subjects.

In 1946 an Iron and Steel Engineers Group was formed to provide a forum for discussion on engineering problems in iron and steelworks.

Close relationship is maintained with other technical and scientific bodies. The Institute of Metals occupies offices at 4 Grosvenor Gardens and collaborates in the organization of many of the Special Meetings and in the maintenance of the Joint Library ; in 1945 the Councils of the two Institutes participated jointly in the formation of the Institution of Metallurgists. Twelve local technical societies in England are affiliated to The Iron and Steel Institute, and many metallurgical societies outside the U.K. enjoy the status of Kindred Societies. Very close collaboration is maintained between the Institute and the British Iron and Steel Research Association : this Association was formed in 1944 to take over the work formerly undertaken by the Joint Research Committees of the Institute and the British Iron and Steel Federation.

A former Vice-President of the Institute, Dr. W. H. Hatfield, F.R.S., is commemorated by the Hatfield Memorial Lecture, which is presented annually, the Lecturer being selected by a Committee on which the Institute is represented. A number of medals and prizes are awarded annually by the Council of the Institute, the most important of these being the Bessemer Gold Medal, endowed in 1873 by the late Sir Henry Bessemer. The Sir Robert Hadfield Medal, the Williams Prize, and the Ablett Prize are also awarded annually, and an Andrew Carnegie Gold or Silver Medal may be awarded to the author of the best Andrew Carnegie Research Report of the year. These reports are the result of work carried out by recipients of grants from the Andrew Carnegie Research Fund, which is administered by the Institute.

The main publication of The Iron and Steel Institute is the *Journal*, which has been published monthly since 1947. Special Reports are published from time to time, and a Bibliographical Series is prepared by the Information Department. The Institute also undertakes the production of the *British Welding Journal* on behalf of the Institute of Welding and the British Welding Research Association, and the *Transactions of the Society of Instrument Technology* on behalf of the Society.

The Joint Library has been in operation since 1938 and, together with the Information Department, it renders most useful service to all members.

THE INSTITUTE OF METALS

The Institute of Metals—technical and scientific society of the non-ferrous metal industries—was founded in 1908 to promote the science and practice of non-ferrous metallurgy in all its branches, and to facilitate contacts and the exchange of ideas among metallurgists, engineers, physicists, chemists, etc. Its membership is international and, out of a total of over 4400, over one-third of its members are resident outside the United Kingdom.

In his presidential address, the first President, Sir William White, the distinguished naval architect, referred to the importance that many firms in the industry attached to secrecy regarding their processes of manufacture, and he looked to the day when those who had the control of works and the direction of processes of manufacture would voluntarily assume a more generous attitude in the general interest of progress in the industry. There is no doubt that The Institute of Metals, in the course of its existence, has played a very large part in bringing about a more enlightened attitude in this respect and it has had a great influence in stimulating, and disseminating the results of, scientific investigations that have brought about tremendous changes in processes of manufacture in the industry.

The main work of the Institute consists of the publication of a monthly periodical (free to all members) in which are included the *Journal, Metallurgical Abstracts*, and the *Bulletin* (each of which are separately bound and indexed); the publication of monographs; and the organization of scientific and technical meetings and symposia for the presentation and discussion of papers. The *Journal*, now in its eighty-third volume, contains papers on original work, first-class reviews of knowledge in particular fields, addresses, lectures, and reports of symposia and discussions. Quite apart from the membership, it has a very wide circulation outside the British Isles. The abstracts were originally printed in the *Journal*. From 1934, however, they have been separately published in *Metallurgical Abstracts*. This new series is in its twenty-second volume. The abstracts, which are of the 'informative' type, are recognized to be the most comprehensive and authoritative in the world in their own field. The books in the Monograph series are written by acknowledged authorities and some have passed through several editions.

In 1956, the Institute will begin the publication of a new quarterly periodical entitled *Metallurgical Reviews*, the object of which will be to provide for the non-specialist authoritative, critical, and interpretative reviews of knowledge gained in various fields of interest to metallurgists. It is believed that this new periodical will meet a real need.

There are six Local Sections of the Institute in industrial centres; in other centres the needs of members are met by co-operation with kindred local societies. Corresponding Members have been appointed to represent the Institute in twenty-one countries. In the U.S.A. there are three Corresponding Members—Professor Morris Cohen, Professor R. F. Mehl, and Dr. R. A. Wilkins, and in Canada there are also three—Dr. G. S. Farnham, Professor F. A. Forward, and Professor G. Letendre.

Another function of the Institute is the organization of educational tours for students in centres of metallurgical interest in Great Britain and other parts of Europe.

Annual Awards of the Institute are: (*a*) The Institute of Metals Medal in platinum, in recognition of very distinguished services to non-ferrous metallurgy; (*b*) the Rosenhain Medal, in recognition of outstanding achievements in the field of physical metallurgy; (*c*) the Capper Pass Awards of £100, for authors of papers on processes or plant used in the fabrication of non-ferrous metals and alloys; and (*d*) the W. H. A. Robertson Medal and Premium, for authors of papers dealing with the engineering side of non-ferrous metal production.

In recent years, two special Committees have been set up by the Council to stimulate interest in, and to arrange meetings on, matters relating to particular fields of interest, viz. the Metal Physics Committee and the Metallurgical Engineering Committee, and recently one has been formed to concern itself with metallurgy in the field of atomic energy.

After nearly 50 years of service, the Institute has undoubtedly more than justified the hopes of its founders, and it looks forward with confidence to greater expansion and new opportunities of service to the science and practice of metallurgy.

The Institute, whose Secretary is Lieut.-Colonel Charles Guillan, T.D., has its headquarters at 4 Grosvenor Gardens, London, S.W.1, in the same building as its sister society, The Iron and Steel Institute, with whom it maintains a Joint Library.

BIOGRAPHIES

Co-Chairmen of American Committee

James B. Austin is a graduate of Lehigh University, where he received the degree of Chemical Engineer. He studied at Yale University, and was awarded the degree of Ph.D. in 1928.

After leaving Yale, Dr. Austin joined the newly-formed United States Steel Laboratories, Kearny, N.J. He was made Assistant Director of the Laboratories in 1944, and two years later he was appointed Director in Charge. He is now Assistant Vice-President for Fundamental Research.

In 1946, Dr. Austin was invited to present the Campbell Memorial Lecture at the Annual Meeting of the American Society for Metals. He served a two-year term as a Trustee of the Society, and in 1952 was made Vice-President. He was elected to serve as President for the Session 1953–1954. He is also currently President of the A.S.M. Foundation for Education and Research.

Leo F. Reinartz was born in East Liverpool, Ohio, and received his education at the Carnegie Institute of Technology where he was awarded the degree of B.S. in 1909.

In the same year Mr. Reinartz joined the Armco Steel Corporation, with whom he has spent his whole industrial career. His first post was as a chemist at the Middleton Works; during this time he studied open-hearth methods, and his next appointment was as open-hearth foreman. He then became successively Assistant Superintendent and Superintendent of the Open-Hearth Department, and in 1923 was appointed Assistant General Superintendent. In 1930 he became Works Manager of the Company's East Works, and eight years later he took up the post of Divisional Manager of the Middleton and Hamilton Plants. Since 1951 he has been a Vice-President of the Company, in charge of special operating developments.

Mr. Reinartz is a member of the American Iron and Steel Institute, and of the Iron and Steel Engineers Association. He has been a member of the American Institute of Mining and Metallurgical Engineers for many years, and served as Chairman of the National Open-Hearth Conference for 18 years. He served as Vice-President of the Institute from 1945 to 1948, has been a Member of the Board of Directors, and was elected to serve as President for 1954.

American Institute of Mining and Metallurgical Engineers

President

H. DeWitt Smith was born at Plantsville, Conn., in 1888, and was educated at Yale University, where he was awarded the degree of Ph.B. in 1908, and that of E.M. in 1910.

Members of the American Committee

Robert S. Archer

John Chipman

and
James B. Austin
William H. Eisenman
Ernest O. Kirkendall

Clyde Williams

and
Leo F. Reinartz
George A. Roberts

John J. Golden

Howard Biers

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American Society for Metals

Other Members of Board of Trustees, Past-Presidents, and Officers

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Walter Crafts

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Adolph O. Schaefer

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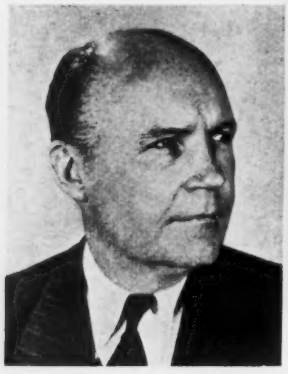
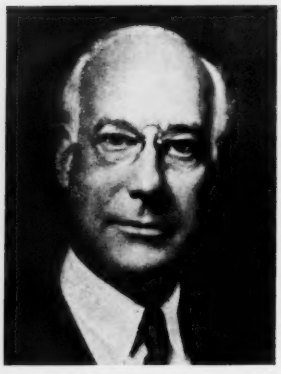


Francis B. Foley



Bradley Stoughton

Herbert J. French

PAST-PRESIDENTS

Frank P. Gilligan

FORMER CHAIRMEN OF IRON AND STEEL DIVISION

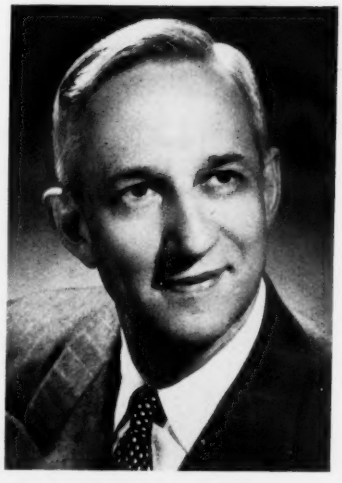
John S. Marsh

Herbert W. Graham

Edward H. Robie

and
Francis B. Foley

SECRETARY EMERITUS

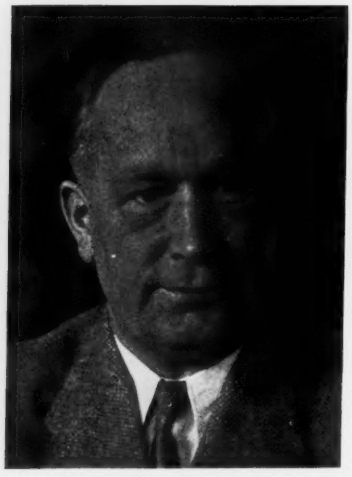


Louis R. Berner

FORMER CHAIRMEN OF OPEN-HEARTH STEEL COMMITTEE

Alvin H. Sommer

Presidents of European Metallurgical Societies



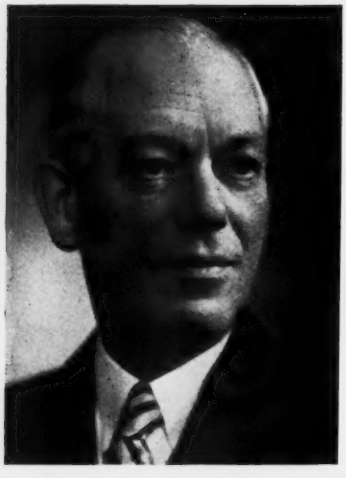
Hermann R. Schenck

Raoul de Vitry

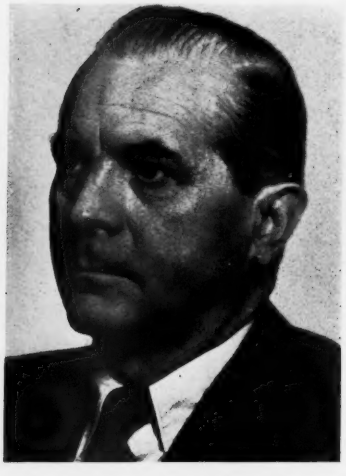
and
Dr. Maurice Cook

François Perot

and
Sir Charles Bruce-Gardner



Evert Wijkander



Paul Brenner

Members of European Committee

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E. L. Dupuy

Bernhard Trautmann

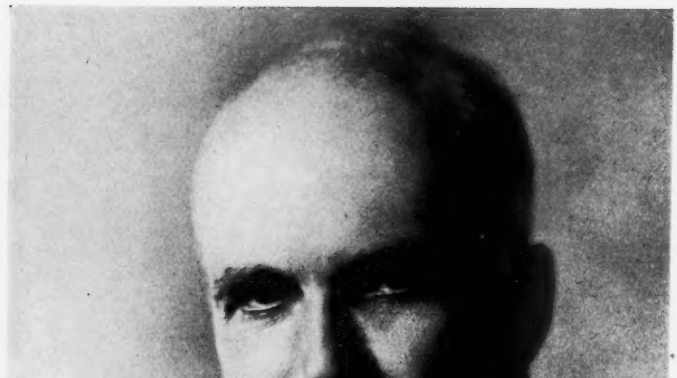
Kenneth Headlam-Morley

Pierre Coheur

Kurt Thomas

Sven Fornander

and
Howard Biers



Sir Lawrence Bragg, Kt., O.B.E., M.C., F.R.S.

Inaugural Lecturer

SIR LAWRENCE BRAGG, the son of the late Sir William Henry Bragg, O.M., K.B.E., F.R.S., was born at Adelaide, South Australia, in 1890. He was educated at St. Peter's College, Adelaide, and at Adelaide University, where he graduated with the degree of B.Sc. He came to the U.K. as an Allen Scholar at Trinity College, Cambridge, and obtained the degree of M.A.

From 1914 until 1919, Sir Lawrence was a Fellow and Lecturer in Natural Sciences at Trinity College. During this time he was awarded the Barnard Medal and the Nobel Prize for Physics, the latter being awarded for work carried out with his father on X-rays and crystal structure. He was next appointed to the Chair of Physics at the University of Manchester, a position which he held until 1937, when he became Director of the National Physical Laboratory. In the following year he was appointed Cavendish Professor of Experimental Physics at Cambridge University. Since 1953 he has been Fullerian Professor of Chemistry at the Royal Institution, and Resident Professor and Director of the Davy Faraday Laboratory of the Institution.

Sir Lawrence is the recipient of honorary D.Sc. degrees from the Universities of Dublin, Leeds, Manchester, Durham, Lisbon, Paris, Brussels, and Liege. He was also awarded the honorary degree of Ph.D. of Cologne University, and that of LL.D. of St. Andrews.

A Past-President of the Institute of Physics, Sir Lawrence is an honorary member of many scientific associations in the U.K., France, Sweden, Holland, Belgium, the U.S.A., and China. During the First World War he served as a Technical Advisor on Sound Ranging in France, with the rank of Major; in World War II he was a member of the Scientific Advisory Council of the Ministry of Supply. He is a recipient of the Hughes Medal of the Royal Society and the Roebling Medal of the Mineralogical Society of America.

Sir Lawrence is to deliver the Inaugural Lecture of the Joint Metallurgical Societies' Meeting in Europe, in London on 1st June. He will speak on " X-Ray Analysis and the Structure of Metals ".

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Mr. Smith began his industrial career as an engineer with J. E. Spurr, Inc. in the western parts of the United States and in Mexico. His next appointment took him to Alaska, where he was successively Foreman, Mine Superintendent, and Assistant Manager to the Kennecot Copper Corporation. He then joined United Verde Copper Company, first as Mine Superintendent, and later as General Superintendent. In 1924 he became an engineer in the Industrial Department of the New York Trust Company ; three years later he returned to United Verde to become Sales Manager. In 1930 he joined his present company, Newmont Mining Corporation, as an engineer ; he became a Director and Vice-President in 1947. He retired from the Vice-Presidency in 1953, but is still a member of the Board. In addition he is still actively interested in South African copper mining and is Chairman of the Board of the O'okiep Copper Company Limited, and Consulting Engineer for the Tsumeb Corporation Limited, and is also a Member of the Executive Committee of the Phelps Dodge Corporation and the St. Joseph Lead Company. He has been a prominent member of the American Institute of Mining and Metallurgical Engineers for many years, and serves as its President for the Session 1955–56.

Past-President

Clyde Elmer Williams was born at Salt Lake City in 1893. He was educated at the University of Utah, where he obtained the degree of B.S. in 1915, and was awarded that of honorary D.Sc. in 1946. He was also awarded the honorary degrees of D.Sc. of the Case Institute of Technology (1945), and of the Ohio State University (1951), D.Eng. of the Michigan College of Mining and Technology (1949), and LL.D. of Marietta College (1955).

On leaving the University of Utah, Dr. Williams worked as a chemist in a mining and smelting concern, until 1917, when he took up research work for the U.S. Bureau of Mines. His next appointment was as a research chemist with the Hooker Electro-Chemical Company at Niagara Falls. In 1920 he returned to the U.S. Bureau of Mines as Metallurgist and Superintendent of Research at its Northwest Experimental Station, which appointment he held until 1924, when he was commissioned by the Argentine Government to survey Argentinian iron and fuel resources. He then became Chief Metallurgist to the Columbia Steel Corporation.

Dr. Williams joined the Battelle Memorial Institute in 1929. He has been Director of the Institute since 1934, Trustee since 1951, and President since 1955.

During the Second World War Dr. Williams served on numerous committees for the Army and Navy Munitions Board, the Council of National Defense, the National Academy of Science, the National Research Council, the Joint Engineers Board, and the Department of Commerce. He has also been a member of the National Advisory Committee for Aeronautics, and Chairman of the Materials and Metals Panel, Research and Development Board of the National Military Establishment. A member of the Board of Managers of the New York State College of Ceramics and of the National Research Council Committee on Engineering and Industrial Research, he is also a member of the Board of Directors of Philadelphia Fund, Inc. He holds membership of many technical societies, including the American Ceramic Society, the American Society of Mechanical Engineers, the American Iron and Steel Institute (of which he is a medallist), the Society for Chemical Industry, and, in Great Britain, the Newcomen Society and The Iron and Steel Institute. He is a Past-President of the American Institute of Mining and Metallurgical Engineers and has held the Chairmanship of its Iron and Steel Division, and also serves on the Finance Committee of the American Society for Metals.

During the English Section of the Joint Metallurgical Societies' Meeting in Europe, Dr. Williams will represent the A.I.M.E. during the absence of the President.

Secretary

Ernest O. Kirkendall was born at East Jordan, Michigan, in 1914. He received his technical education at Wayne University, where he obtained the degree of B.S. in Chemical Engineering in 1934, and at the University of Michigan, where he was awarded the degrees of M.Sc. in Metallurgical Engineering in 1935 and D.Sc. in 1938. He held the post of Instructor in Metallurgical Engineering at Wayne University from 1937 until 1941, when he was appointed Assistant Professor of Metallurgical Engineering. He held this appointment until 1946.

From 1938 until 1945 Mr. Kirkendall acted as Metallurgical Consultant to the Progressive Welder Company, Detroit. In the following year he joined the American Institute of Mining and Metallurgical Engineers as Assistant Secretary ; his appointment as Secretary was made earlier this year.

Secretary Emeritus

Edward H. Robie was born at Whitney Point, N.Y., in 1886, and was educated at Cornell University, and at the University of Michigan, where he obtained the degree of B.Ch.E.

Mr. Robie's industrial career began when he joined the Westinghouse Electric and Manufacturing Company. His next appointment was as a chemist and advertising engineer with the Harrison Safety Boiler Works, Philadelphia. In 1913 he joined the Smelting Department of the Canadian Copper Company, and two years later he became Assistant Metallurgist with the International Nickel Company. In this post he was in charge of the Company's test work and sampling mill. In 1919 he was appointed Assistant Editor of the *Engineering and Mining Journal*; later he became Associate Editor, and also Associate Editor of the *Engineering and Mining World* and *Metal and Mineral Markets*.

In 1932 Mr. Robie joined the American Institute of Mining and Metallurgical Engineers as Assistant Secretary, and also took up the post of Editor of the Institute's Monthly Journal. He became Secretary in 1949, and held this appointment until his retirement earlier this year.

Former Chairmen of Iron and Steel Division

Herbert W. Graham was born at Johnstown, Pa., in 1891, and received his technical education at Lehigh University.

Since leaving the University in 1914, Mr. Graham has spent the whole of his career with the Jones and Laughlin Steel Corporation at Pittsburgh. He has held various operative, technical, and executive positions, and in 1947 he was appointed Vice-President in Charge of Research and Director of Technology. He has recently retired from this appointment, and is now Consultant on Technology to the Corporation.

Mr. Graham has carried out research into and written papers on such subjects as the machinability of free-cutting steels, the embrittlement of steel, and the Bessemer process, and he was responsible for the conception and development of a series of high-sulphur intermediate manganese steels. He has visited South America on a tour of industrial research, and was Chairman of the first steel group of the Nelson Mission to China in 1944–45. During the Second World War he acted as steel consultant to the Office of Production Management and to the War Production Board.

A co-founder and senior Past-President of the Industrial Research Institute, Mr. Graham is a member of the American and British Iron and Steel Institutes, the Society of Automotive Engineers, the American Association for the Advancement of Science, the American Society for Metals, and the National Research Council. A prominent member of the American Institute of Mining and Metallurgical Engineers, he served as Chairman of the Iron and Steel Division in 1943, and was invited to give the Howe Memorial Lecture in 1947.

John S. Marsh was born in Pittsburgh in 1905. After graduating from Pennsylvania State University in 1927, he was employed by the Aluminum Co. of America as a pyrometric engineer working on heat transfer problems of aluminium and its alloys. For a year he supervised the development of precision optical instruments for the Keuffel and Esser Co. before joining the Alloys of Iron Research of the Engineering Foundation, New York, as a physical metallurgist. In 1942 he joined the Bethlehem Steel Co., where he was first in charge of the steelmaking division of the research department. He is now Assistant Manager of Research.

The author of several monographs, books, and technical papers, Mr. Marsh became a member of the American Institute of Mining and Metallurgical Engineers in 1931, and served as Chairman of the Iron and Steel Division until earlier this year. He is also a member of the Executive Board of the Open-Hearth Steel Committee, and is active on various other A.I.M.E. assignments and in several governmental advisory groups. In 1950 he was awarded the Robert W. Hunt Medal, and this year he was chosen to be the Howe Memorial Lecturer.

Former Chairmen of O.H. Steel Committee

Alvin Henry Sommer was born at Peoria, Illinois, in 1900. He was educated at the Box Elder High School, Utah, Bradley Academy, Peoria, and the Bradley Polytechnic Institute, where he obtained his Associateship in Science.

From 1920 until 1926 Mr. Sommer served as Superintendent with the Sommer-Baer Drainage Company, Ogden, Utah. He then joined the Keystone Steel and Wire Company, Peoria, as observer in the Rolling Mills, and a year later he became Assistant to the Superintendent of the Company's Steel Mills. He was subsequently appointed Superintendent of the Steel Post Department (1932), Superintendent of Steel Plant (1935), and in 1942 he was made a Director of the Company. He is now Vice-President and General Superintendent.

Mr. Sommer is a member of the American Institute of Mining and Metallurgical Engineers, and served as Chairman of the Open-Hearth Steel Committee of the Iron and Steel Division in 1951–52.

Louis Rolland Berner was born at Indianapolis, Indiana, in 1896. He received his technical education at the University of Illinois, graduating in chemical engineering.

From 1918 until 1920 Mr. Berner was employed as an analyst and metallurgist with the Inland Steel Company. He was then responsible for the establishment and development of a Metallographic Department of the Company, although he was actively engaged in other metallurgical research during this period. In 1927 he was appointed Assistant Superintendent of O.H. Plant; ten years later he became Superintendent, and in 1947 he became Superintendent of Steel Production.

A member of the American Institute of Mining and Metallurgical Engineers, Mr. Berner served as Chairman of the Open-Hearth Steel Committee of the Iron and Steel Division in 1953–54.

American Society for Metals

President

George A. Roberts was educated at the United States Naval Academy (1937–1939), and at the Carnegie Institute of Technology, where he was awarded the degree of B.Sc. in Metallurgy in 1939. He remained at the Institute as teaching assistant in physical metallurgy and ferrous metallography, and obtained the degree of M.Sc. in 1941.

In 1940 Mr. Roberts joined the Vanadium-Alloys Steel Company at Latrobe, Pennsylvania. In the same year he became a graduate fellow of the Company, and in 1942 was awarded the degree of D.Sc. of the Carnegie Institute. He was then appointed Research Metallurgist to the Company, and is now the Company's Vice-President, Technology.

After completing a two-year term as a National Trustee of the American Society for Metals, Mr. Roberts was elected Vice-President for the Session 1954–55, and serves as the Society's President this year. He is the co-author of a book, *Tool Steels*, published by the Society.

Secretary

William H. Eisenman was born in Jamestown, Ohio, and was educated at Kenyon College, Stanford University, Morningside College, and Ohio State University.

He began his career as Principal of the High School at Olathe, Kansas, and was successively Head of the Chemistry Department of Racine College, and Superintendent of Public Schools at Elmhurst, Illinois. He then became National Secretary of the American Society for Steel Treating, which later became the American Society for Metals. He is a founder-member of the latter Society, and has been its Secretary for 37 years, during which time the membership has grown from 200 to 24,000.

Mr. Eisenman has directed the National Metal Congress and Exposition for the past 37 years, and has also directed the Western Metal Congress and Exposition since the first one held in 1929. He has served in many technical and civic organizations, having been at some time Secretary of the Metal Treating Institute and of the Metals Group of the National Research Council.

Treasurer

William A. Pennington received his technical education at Iowa State College, where he graduated and later was awarded the degree of Ph.D. His first appointment was Head of the Department of Mathematics at Union University, and he next joined the Armco Steel Corporation as a research engineer. He spent some time at the Mellon Institute in Pittsburgh as an industrial fellow, and then became Chief Chemist and Chief Metallurgist to the Carrier Corporation, Syracuse, N.Y. At present he holds the Professorship of Metallurgy at the University of Maryland.

Dr. Pennington, who was the recipient of the Henry Marion Howe Medal for 1947, has played an active part in the work of the American Society for Metals for many years. He was elected Treasurer of the Society in 1953.

Vice-President

Adolph O. Schaefer received his technical education at the University of Pennsylvania, graduating in Chemical Engineering in 1922.

Mr. Schaefer has spent his entire business career with the Midvale Company, Nicetown, Pa. He joined the Company in 1922 as a Research Metallurgist, and two years later was appointed Assistant Engineer of Tests. His appointment as Assistant Production Manager followed thirteen years later, and in 1942 he became Executive Metallurgical Engineer. He was promoted

Executive Engineer in 1945, and five years later became Assistant to the Executive Vice-President. He took up his present appointment as Vice-President in Charge of Engineering and Manufacturing in 1951.

During the Second World War Mr. Schaefer was closely concerned with many of the Government activities associated with the production of ordnance materials, and he is still a member of the Government's Advisory Committee for Guns. He has been a member of the American Society for Metals for many years, has served on many of the Society's National Committees, and is a Past-Chairman of the Philadelphia Chapter. He served as a National Trustee from 1952 until 1954, when he was elected Vice-President.

Trustees

George M. Young was born in Saskatoon and received his technical education at the University of Saskatchewan and at McGill University, where he graduated in Metallurgical Engineering in 1930.

After graduation, Mr. Young joined the technical staff of the Aluminium Company of Canada, Limited, at Toronto, as Metallurgical Assistant. In 1932 he was appointed Works Chief Metallurgist. When the construction of a new sheet extrusion and forge plant for the Company was completed in Kingston, Canada, Mr. Young was transferred to Kingston to organize the Technical Department. He remained in charge as Works Chief Metallurgist until 1944, when he became Chief Metallurgist to the Company's General Technical Department. Two years later he transferred to the Head Office in Montreal to become Technical Director.

Mr. Young has served as Chairman of the Montreal Chapter of the American Society for Metals, and was appointed a Trustee of the Society in 1953.

Walter Crafts received his education at Yale University, where he was awarded the degree of B.A. in 1924, and at the Massachusetts Institute of Technology, where he was awarded the degree of M.Sc. two years later.

His first industrial appointment was in the Metallurgical Department of the South Works, Illinois Steel Company. Since 1929 he has been associated with the Union Carbide and Carbon Research Laboratories, and is now Associate Director of Research in the Metals Research Laboratories of the Electro Metallurgical Company, a division of Union Carbide and Carbon Corporation, Niagara Falls.

The author of several papers on deoxidation and the effects of alloys in steel, Mr. Crafts has served as Chairman of the Buffalo Chapter of the American Society for Metals. He has been a member of several Committees of the Society, and was appointed to serve a two-year term as National Trustee in 1954.

Karl L. Fetters, a native of Ohio, was educated at Alliance High School, and at the Carnegie Institute of Technology, where he received his degree in Metallurgical Engineering. He was later awarded the degree of D.Sc. by the Massachusetts Institute of Technology, where he held a Research Assistantship.

Mr. Fetters spent some time on the teaching staff of the Carnegie Institute of Technology. In 1943 he joined the Youngstown Sheet and Tube Company as Metallurgical Engineer for the Operating Vice-President, and in 1950 he took up his present appointment as Assistant to the Vice-President in Charge of Operations.

An active members of the American Society for Metals, Mr. Fetters has served as Chairman of the Educational Committee and was invited to give the first Marcus A. Grossman Lecture to the Mahoning Valley Chapter. He was elected to serve a two-year term as National Trustee of the Society in 1954.

Robert J. Raudebaugh received his technical education at the Carnegie Institute of Technology and was awarded the degree of B.S. in Chemical Engineering in 1932. The degree of Ph.D. was conferred upon him by Purdue University in 1945.

From 1939 to 1944 Dr. Raudebaugh was Instructor in Physical Metallurgy at Purdue University. He then joined the staff of the University of Rochester, where he was in charge of graduate and undergraduate work in metallurgical engineering. In 1948 he was appointed Professor of Metallurgical Engineering at the Georgia Institute of Technology. During his career Dr. Raudebaugh has also spent six years doing research work with the Armco Steel Corporation. In 1952 he spent 3 summer months while on vacation as a member of the staff of the Research Laboratory of the International Nickel Company. He rejoined the International Nickel Company permanently in 1954.

The author of a book "*Nonferrous Physical Metallurgy*", Dr. Raudebaugh has taken an active part in the work of the American Society for Metals since 1933, and in 1953 he was appointed to serve a two-year term as a Trustee of the Society.

Past-Presidents

Bradley Stoughton was born in New York City, and received his technical education at the Sheffield Scientific School, Yale University, and at the Massachusetts Institute of Technology.

During his career Professor Stoughton has filled various positions, including Instructor at the Massachusetts Institute of Technology, assistant to Professor H. M. Howe at Columbia University, and Acting Head of the School of Mines, Department of Metallurgy, Columbia University. On the industrial side, he has worked as a metallurgist with the Illinois Steel Company, Chief of the Cost Statistics Division of the American Steel and Wire Company, and Manager of the Bessemer Steel Department of Benjamin Atha and Company. In 1925 he became Professor of Metallurgy and Dean of Engineering at Lehigh University, retiring in 1942.

The author of several books and papers on various aspects of engineering and metallurgy, Professor Stoughton is a member of the American Society for Metals, the American Institute of Mining and Metallurgical Engineers, the American Iron and Steel Institute, the American Society for Testing Materials, and the American Foundrymen's Association. In Great Britain he is a Member of The Iron and Steel Institute. He is a Past-President of the American Society for Metals, the Electrochemical Society, and the Yale Engineering Association.

Herbert J. French was born in New York City in 1893, and received his technical education at the School of Mines, Columbia University, graduating as a Metallurgical Engineer in 1915.

After gaining practical experience in western U.S.A., Mr. French joined the General Vehicle Co. as a metallurgical engineer. During the First World War he was engaged in metallurgical work for the Bureau of Aircraft Production, and in 1919 he joined the metallurgical staff of the Bureau of Standards, where he held various appointments before becoming Assistant Chief of the Division of Metallurgy. In 1929 he took up an appointment in the Research Laboratories of the International Nickel Company. Since 1947 he has served as Vice-President of the Company and Assistant Vice-President of the International Nickel Co. of Canada Ltd.

During the Second World War he held the post of senior technical consultant in the iron and steel branch of the War Production Board, and later became Assistant Director of the metallurgical branch.

The author of several technical books and papers, Mr. French is a recipient of the Henry Marion Howe Medal, and the Lincoln Gold Medal Award, and has been a Campbell Memorial Lecturer and a Burgess Memorial Award Lecturer. He is a member of the American Iron and Steel Institute, the American Society for Testing Materials, and the A.I.M.E. He is a Past-President of the A.S.M.

Walter E. Jominy graduated in Chemical Engineering from the University of Michigan in 1915, and in the following year was awarded the degree of M.S.

His first appointment was as a metallographer with the Studebaker Corporation ; then in 1917 he became associated with the U.S. Bureau of Aircraft Production, where he became Senior Metallurgical Inspector. From 1918 to 1920 he worked as a metallurgical engineer with the Packard Motor Car Company, and then returned to the Studebaker Corporation to take charge of the chemical and metallurgical laboratories. In 1923 he joined the Department of Engineering Research at the University of Michigan as a research engineer. He remained at the University until 1931, when he took up a post as research metallurgist with the A. O. Smith Corporation. He then spent some years in the Research Laboratories Division of the General Motors Corporation before taking up his present appointment as Staff Engineer to the Chrysler Corporation in 1941.

Mr. Jominy was the recipient in 1944 of the Albert Sauveur Achievement Award presented by the American Society for Metals, and was cited for a Distinguished Service Award at the Metal Show in 1948. He was elected President of the Society for 1950–51. In 1953 he received a citation from the University of Michigan for outstanding contributions to developments in the field of engineering.

Francis B. Foley, a graduate of Girard College, began his metallurgical career in the Open-Hearth Department of the Midvale Company in 1905. He joined the Research Staff of the Company two years later, and remained there until 1917. He then spent a short time at the University of Minnesota, where he taught metallography, before becoming a member of the War Materials Investigation Group of the U.S. Bureau of Mines in 1918. In the following year he became Head of the Iron and Steel Division. As a metallurgist with the Bureau, he had the privilege of collaborating with the late Dr. Henry Marion Howe for a year ; he then carried out research into drill steel for mines and oil wells, and later into blast-furnace operation. In 1924 he joined the Lucey Manufacturing Corporation as a metallurgist, and two years later he returned to the Midvale Company as Superintendent of Research. Since 1949 he has been with the International Nickel Company as Consulting Metallurgist.

A member of the American Institute of Mining and Metallurgical Engineers (of which he was a Director from 1950 until 1952), of the American Chemical Society, and, in Great Britain, of The Iron and Steel Institute, Mr. Foley joined the American Society for Metals in 1920. He is a Past-Chairman of the Philadelphia Chapter, and has served as Trustee, Treasurer, and Vice-President of the Society. He was elected as President for the year 1947–48. He is a Fellow of the Institute of Chemists, and is currently Chairman of the Joint A.S.T.M.–A.S.M.E. Committee on the Effect of Temperature on the Properties of Metals.

Frank P. Gilligan began his engineering career in 1903, when he became a laboratory assistant in the consulting engineering office of Henry Souther. He has spent the whole of his career in this activity, and is now Secretary-Treasurer of the Henry Souther Engineering Company at Hartford, Connecticut.

With the advent of the automobile, Hartford became one of the centres of early development in this field. Mr. Gilligan played a prominent part in the development and heat-treatment of the automotive steels, and served for many years as Chairman of the Iron and Steel Division of the Society of Automotive Engineers. During his association with Mr. Souther he was intimately associated with such eminent metallurgists as Howe, Campbell, Sauveur, Richards, and White.

Mr. Gilligan has been a member of the American Society for Metals for 35 years, and was the second President of the Society in 1921. In Great Britain he is a Member of The Iron and Steel Institute and The Institute of Metals.

Other Members of the American Committee

Robert S. Archer was born near Denver, Colorado, in 1895. He received his education at Cass Technical High School, Detroit, and the University of Michigan, where he was awarded the degree of Bachelor of Chemical Engineering in 1916, and that of M.Sc. in the following year, and where he worked as assistant to the late Professor Edward DeMille Campbell.

On leaving the University, Mr. Archer joined the Metallurgical Department of the Bureau of Aircraft Production in Detroit. In 1919 he began an association with the Aluminum Co. of America that was to last eleven years, and in 1925 he became Head of the Cleveland Section of the Aluminum Research Laboratories. During this time he became widely known as an authority on aluminium alloys. In 1930 he became Director of Metallurgy to the A. O. Smith Corporation, and in 1934 he joined the Republic Steel Corporation as Chief Metallurgist for the Chicago district. Since 1944 he has been Chief Metallurgical Engineer of the Climax Molybdenum Co.

Mr. Archer was closely connected with the American Institute of Mining and Metallurgical Engineers when he served as Chairman of the Committee on Data Sheets of the Institute of Metals Division. He also played a prominent part in the development of data sheets on non-ferrous metals for the National Metals Handbook. He has been a member of the American Society for Metals for many years, and served as its President for the Session 1934–35.

Howard Biers was born in New York in 1904. He received his technical education at the University of Virginia, where he was awarded the degree of B.S., and the Massachusetts Institute of Technology, where he obtained the degree of Master of Science. In 1954 he was awarded the degree of Dr. mont. (Doctor of Mining and Metallurgical Sciences) of the University of Mining and Metallurgy, Leoben, Austria.

From 1927 to 1930 Dr. Biers worked as a research metallurgist with the Union Carbide and Carbon Research Laboratories, Inc. He spent the next ten years in Europe, as a consulting engineer in Paris, Brussels, and London, and then became Technical Advisor to the Metals Controller, Department of Munitions and Supply of the Canadian Government, and a member of the Canadian Government's Technical Advisory Committee. During this time he was also Canadian Chairman of the Ferro Alloy Committee of the War Production Board, a member of the joint U.S.–United Kingdom Canadian Metallurgical Mission, and Special Advisor to the Department of Trade and Commerce. Since 1948 he has been Consulting Engineer to the Union Carbide and Carbon Corporation.

Dr. Biers holds membership of many American and foreign societies. He is a member of the Associacaõ Brasiliera de Metais, the Spanish Iron and Steel Institute, Verein Deutscher Eisenhüttenleute, and Eisenhütte

Oesterreich, an honorary member of the Spanish Institute of Welding, and U.S. delegate on the Commission Permanente Internationale de l'Acetylene. He was elected to serve as President of the International Institute of Welding for the Session 1954–57. In Great Britain he is a Fellow of the Institution of Metallurgists and a Member of The Iron and Steel Institute and The Institute of Metals. In America he is a member of the American Welding Society, the American Institution of Mining and Metallurgical Engineers, and the American Society for Metals.

John Chipman was born in Florida. He graduated from the University of the South and holds the degrees of B.S. and D.Sc. from that University, and M.S. from the State University of Iowa. He was awarded the degree of Ph.D. of the University of California in 1926.

Dr. Chipman became Assistant Professor of Chemistry at the Georgia School of Technology in 1926 ; he left in 1929 to become a Research Engineer at the University of Michigan. From 1934 until 1937 he was Associate Director of the Research Laboratories of the American Rolling Mill Co. (now the Armco Steel Corporation). He then joined the staff of the Massachusetts Institute of Technology as Professor of Process Metallurgy, and took up his present appointment as Head of the Department of Metallurgy in 1946.

The recipient in 1934 of the Howe Medal of the American Society for Metals, and in 1938 of the Hunt Award of the American Institute of Mining and Metallurgical Engineers, Dr. Chipman was elected President of the former Society for the Session 1951–52. Earlier this year he was awarded the Bessemer Gold Medal of The Iron and Steel Institute in recognition of his distinguished contributions to the knowledge of the physical chemistry of steelmaking. In 1954 he was awarded the Brinell Medal of the Royal Swedish Academy of Engineering Sciences (Ingeniörsvetenskapsakademien), awarded for outstanding achievements in metallurgy. Dr. Chipman was the first non-Swedish recipient of this medal.

John J. Golden was born in 1897 in Chicago, where he received his education, and later attended the University of Chicago.

Mr. Golden's entire industrial career has been spent with the United States Steel Corporation. He joined the South Chicago Plant of the Company in 1911, and in 1933 became Open-Hearth Superintendent. Five years later he transferred to the Gary Steel Works of the Company as Superintendent of Steel Production. From 1940 until 1950 he served as Division Superintendent of Steel Production. He then took up his present appointment at Pittsburgh as Assistant to the Vice-President in relation to Steel Production and Central Operations.

Mr. Golden is a member of the American Iron and Steel Institute, the Association of Iron and Steel Engineers, the American Institute of Mining and Metallurgical Engineers, and the American Society for Metals.

European Presidents

The Iron and Steel Institute

Sir Charles Bruce-Gardner, Bt., Chairman of John Lysaght Limited, was born in London and educated at St. Dunstan's College and at Battersea Technical College, afterwards serving his mechanical engineering apprenticeship at the Westinghouse Company's works at Trafford Park, Manchester. On completion of his apprenticeship Sir Charles obtained an appointment with John Summers and Sons, Shotton, as Assistant to the Steelworks Manager and Rolling Mill Manager, afterwards succeeding to the position. Later he became Assistant Works Manager and then Works Manager, and was elected to the Board in 1913.

From 1929 to to 1930 Sir Charles was Chairman of the Iron and Steel Industrial Research Council. At the same time, he became a Member of the Advisory Committee of the Department of Overseas Trade. In 1930 he joined the Bank of England to become Industrial Advisor to the Governors, and was also appointed Managing Director of the Bankers' Industrial Development Company, Limited, and of The Securities Management Trust, Limited, the Bank of England Company. He held the appointment of Chairman of the Iron and Steel Exchange in 1936 and 1937.

In December, 1937, at the request of the Government, Sir Charles left the Bank of England to assist in the Government's air re-armament programme, and was appointed Independent Chairman of the Society of British Aircraft Constructors. He was awarded a Knighthood in 1938, and became a Baronet in 1945. During the Second World War he served on many Government Committees and in a number of executive positions. Towards the end of the war he was appointed by the President of the Board of Trade to the position of Chief Executive for Industrial Reconversion to deal with the industrial problems arising from the change-over from war to peacetime conditions. At the completion of this work he returned to the steel industry and is now a Director of a number of steel companies.

Sir Charles is a Member of Council and of the Executive Committee of the British Iron and Steel Federation. He was elected this year to serve as President of The Iron and Steel Institute for the Session 1955–56.

The Institute of Metals

Maurice Cook was born at Hartlepool in 1897, and graduated with First Class Honours in Metallurgy at Manchester University in 1919. He was subsequently awarded the degrees of Ph.D. (Cambridge) and D.Sc. (Manchester), and Honorary Associateship of the Birmingham College of Technology.

From 1919 until 1921 Dr. Cook was engaged in research and lecturing at the University of Manchester. He then went to King's College, Cambridge, and carried out research in the Goldsmiths' Laboratory. In 1924 he joined the technical staff of C. A. Parsons and Company, Limited; two years later he moved to Kynochs Limited, and in 1938 became Research Manager of the Metals Division of Imperial Chemical Industries Limited. His appointment as a Director followed four years later, and in 1951 he took up his present position as Joint Managing Director.

The author of many papers covering a wide range of non-ferrous subjects, Dr. Cook has served on the General Council of the British Standards Institution, the Inter-Service Metallurgical Research Council, the British Welding Research Council, the Council of the Electrodepositors' Technical Society, and the Metallurgy Committee of the Ministry of Supply. He has also been Chairman of the Midland Metallurgical Societies and President of the Birmingham Metallurgical Society and the Institution of Metallurgists.

He has been a member of The Institute of Metals since 1918, and serves as its President for the Session 1955–56.

Verein Deutscher Eisenhüttenleute

Hermann R. Schenck was born in 1900 at Marburg in Hessen. He was educated in Westphalia and graduated at the Technical University of Aachen in 1923, where he stayed on as lecturer in the physical chemistry of metallurgy. In 1927 he was awarded the degree of Dr.-Ing of the University. Two volumes of a text-book written by him between 1932 and 1934 were published in the English

version in 1945 under the titles: "*Introduction to the Physical Chemistry of Steelmaking.*"

In 1934 Dr. Schenck was appointed steelworks manager at Krupp, Essen, and in 1937 manager at the Charlottenhütte, Niederschelden. In 1942 he became a Director of the Bochumer Verein, Bochum, and until 1951 served on the Board.

Since 1950 Professor Schenck has been Director of the Institute for Ferrous Metallurgy at the Technical University of Aachen, where he also holds the Chair in that subject. He has also been President of the Verein Deutscher Eisenhüttenleute for the last five years.

Deutsche Gesellschaft für Metallkunde

Paul Brenner was born at Stuttgart in 1897. He studied at the Technische Hochschule, Stuttgart, graduating as an engineer in 1923. He was awarded the degree of Dr.-Ing. of the Technische Hochschule, Berlin, in 1928.

From 1923 until 1936, Dr. Brenner held the post of Director of the Institute for Materials Research of the Deutscher Versuchsanstalt für Luftfahrt in Berlin. Since 1937 he has been Director of the Research Institute of the Vereinigten Leichtmetallwerke GmbH., Bonn, and he is also Professor at the Technische Hochschule at Hanover. In 1952 he was elected President of the Deutsche Gesellschaft für Metallkunde.

Société Française de Métallurgie

Joseph Marie Raoul de Vitry d'Avaucourt was born at Lure in 1895, and received his education at the École Polytechnique. He served for a time as an engineer in the Corps des Mines, and during the First World War he held a commission in the Artillery and was awarded the Croix de Guerre.

From 1921 until 1928 Monsieur de Vitry was employed by the Mines de l'Etat. He then joined the Compagnie Pechiney, where he has since remained in the successive appointments of Manager, General Works Manager, and Vice-President and Director-General.

Monsieur de Vitry serves on the Boards of several organizations and is President and Director-General of the Société d'Exploitations et d'Interêts Chimiques et Métallurgiques, and Honorary President of l'Aluminium Français. He is also a Member of the Comité des Prêts du Crédit National. Earlier this year he was elected to serve as President of the Société Française de Métallurgie.

Centre National de Recherches Métallurgiques

François Perot received his technical education at the University of Liège, graduating as a Mining Engineer in 1906, and as an Electrical Engineer in 1908.

After spending some time in the coal and other industries, Monsieur Perot joined S.A. d'Ougrée-Marihaye as Assistant Engineer in the Blast-Furnace Department of the Rodange Works in 1911. He has remained with that Company for the past 44 years, during which time he has held the following appointments: Secretary of the Blast-Furnace Division at Ougrée (1919); Technical Secretary, General Management (1921); Manager (1931); General Works Manager (1933); General Manager (1936). In 1948 he became a Member of the Board of the Company.

Monsieur Perot is a Director of several other industrial concerns, and serves as Chairman of the Board of Directors of the following organizations: La Société d'Opérations Maritimes et Fluviales, Antwerp; S.A. des Fours à Coke de Zeebrugge; le Groupement Belge des Fabricants de fil machine; le Syndicat Belge des Scories Thomas; Van Thiel's Draad-Industrie, Beek-en-Donck; Dikema en Chabot's Handel Maatschappij, Rotterdam; la Centrale d'Affrètement et d'Expédition, Brussels; la Caisse d'Epargne et de Dépôts d'Ougrée; N.V. Ougrée-Handelmaatschappij, The Hague.

An active member of many national steelmaking organizations, Monsieur Perot is President of the Centre National de Recherches Métallurgiques (National Metallurgical Research Centre), the Centre Belgo-Luxembourgeois d'Information de l'Acier (Belgo-Luxembourg Steel Information Centre), and the Commission pour l'Étude de la Construction Métallique (Metallic Structures Committee), and Vice-President of the Groupement des Hauts Fourneaux et Aciéries Belges (Belgian Blast-Furnace and Steelworks Group). A member of the Trustee Committee of the Institut Royal des Sciences Naturelles de Belgique (Royal National Science Institute of Belgium), he also holds the post of Director of the Centre de Documentation Sidérurgique (Steelmaking Documentation Centre) in Paris.

A recipient of the Liège University Medal, Monsieur Perot is a Commander of the Order of Leopold, Commander of the Order of the Crown, and a Chevalier of the Legion of Honour.

Jernkontoret

Evert Wijkander was born at Ramen, Sweden, in 1891. He received his technical education at the Royal Institute of Technology, Stockholm, graduating as a metallurgical engineer in 1912. In 1914 he went to the U.S.A. for two years, where he worked in the Homestead Steelworks, Pittsburgh, and then spent a year in Germany.

Mr. Wijkander's first industrial appointment was as Assistant Melting-Shop Manager with AB Bofors in 1918. Two years later he was appointed Melting-Shop Manager at the Hagfors Steelworks, and in 1924 he became Works Manager of Fagersta Bruks AB, a position which he held for ten years. In 1935 he rejoined the Bofors concern, and a year later was appointed Managing Director, a position which he still holds. He is also President of the Board of Directors of a number of subsidiary companies, and a member of the Boards of several other companies.

Since 1945 Mr. Wijkander has been President of the Swedish Iron and Steel Works Employers' Association; he has also been President of the Swedish Institute for Metal Research since 1949. He has taken an active part in the work of other industrial organizations and is a Member of the Federation of Swedish Industries and of the Swedish Employers' Confederation. Until recently he was also a Member of Council of the Federation of Swedish Mechanical Engineering Industries. He is a member of the Royal Swedish Academy of Military Science, the Swedish Academy of Engineering Sciences, and the Swedish Academy of Naval Science.

Mr. Wijkander became a Member of Council of Jernkontoret in 1938, and was elected President in 1952. He became a Member of the Research Council of Jernkontoret in 1933, and served as President of this Council from 1948 until 1952. He was nominated an Honorary Vice-President of The Iron and Steel Institute in June, 1954.

European Committee

Kenneth Headlam-Morley was born in Cambridge on 24th June, 1901. His father (later Sir James Headlam-Morley, C.B.E., Historical Advisor to the Foreign Office) was the younger son of the late Canon A. W. Headlam, of Whorlton Hall, Co. Durham, a member of a younger branch of a family that has been long established in Teesdale. In 1917 James Wycliffe Headlam and his son and daughter assumed by Royal Licence the additional surname and arms of Morley, a related family which had

old connections with Wharfedale, Swaledale, and Craven in Yorkshire. His mother was Else Sonntag, the younger daughter of Dr. August Sonntag of Lüneburg; she was a gifted musician and, in her youth, had been a pupil of Franz Liszt.

Mr. Headlam-Morley was educated at Rokeby School, Wimbledon, and at Eton College, where he was in Division I, and won the Junior and Senior Rosebery History Prizes and Second Oppidan Prize ; he also rowed, being awarded his Lower Boat Choices and Upper Boats. In 1919 he went up to Oxford with a history scholarship at New College and there read ' Greats ' and History ; for three years he whipped-in to the New College and Magdalen Beagles.

In 1924 he joined the staff of Dorman, Long and Co., Ltd., iron and steel manufacturers, of Middlesbrough. After an extensive training in the secretarial, accountancy, and commercial departments at Head Office, he spent some years gaining experience in almost all departments of the company's works, and also spent some months working underground in the pits. He then joined the Managing Director's Department and later served also for short periods in the By-Products Department and in the Company's London Office.

Mr. Headlam-Morley became Secretary of The Iron and Steel Institute in 1933, and as such was Secretary of the Institute's four Joint Research Committees until they were transferred to the British Iron and Steel Research Association in 1945–46. He was responsible for organizing the Symposium on the Welding of Iron and Steel, held in 1935, and the London Congress of the International Association for Testing Materials, held in 1937. From 1944 to 1947 he served also as Secretary of The Institute of Metals and was Secretary of the Institution of Metallurgists from the foundation of the Institution in 1945 until 1948. He was Secretary of the Joint Committee on Metallurgical Education and of the Joint Committee for National Certificates in Metallurgy from the time these Committees were formed in 1945 until the end of 1954, when the former was dissolved and the secretarial arrangements for the latter were entrusted to the Institution of Metallurgists. During the war he served as Deputy Controller of the Chrome Ore Magnesite and Wolfram, Foundry Bonding Materials, and associated controls of the Ministry of Supply.

Mr. Headlam-Morley has paid many visits to the Continent and has also twice been to Canada and the U.S.A. He was made a Chevalier (Riddare) of the Order of Vasa of Sweden in June, 1954. He is Honorary General Secretary of the European Committee of the Joint Metallurgical Societies' Meeting in Europe, 1955.

Charles Guillan was born in London in 1895. His early training in metallurgy, under Mr. (later Professor) C. O. Bannister, was interrupted by the First World War in which he served from August, 1914, in the Norfolk Regiment. He was twice wounded in the Mesopotamian campaign with the 2nd Battalion of his Regiment.

In 1920, he returned to serve as Assistant to the Secretary of The Institute of Metals. As a result of conversations with Professor R. S. Hutton, an enthusiast in matters concerning the dissemination of scientific knowledge, he immediately set about the task of building up, out of the rather slight and haphazard abstracts section of the *Journal*, a properly organized abstracting system to provide a first-class, reliable, comprehensive, and much-needed service to science and industry. Since then, he has been responsible for nearly all the changes made in the organization of the service and the publication of abstracts, including the change to monthly publication in a separate periodical under the title *Metallurgical Abstracts*. The building up of this service is the achievement that has brought him the most satisfaction.

He was appointed the first Assistant Secretary of the Institute in 1926; Editor of Publications from 1936 to 1946; Editor of Publications and Assistant Secretary from 1946 to 1947; and Secretary and Editor of Publications in 1947. At his request, he relinquished the duties of Editor in 1949, when Mr. N. B. Vaughan rejoined the staff.

Soon after the end of the First World War, he became interested in the Territorial Army, serving in the Queen's Royal Regiment and, from 1938, in the Royal Artillery. He served throughout the Second World War, being promoted Lieut.-Colonel in 1940, and retired from the Army in 1946.

Colonel Guillan is a member of The Institute of Metals, The Iron and Steel Institute, the Société Française de Métallurgie, and Verein Deutscher Eisenhüttenleute.

Kurt Thomas was born in 1900 at Elberfeld. He studied ferrous metallurgy at the Technische Hochschulen of Stuttgart and Aachen, where he graduated in 1923.

His first industrial appointment was at the Rheinische Stahlwerke near Duisburg, which he left in 1925 to join the staff of Verein Deutscher Eisenhüttenleute as editorial assistant under Otto Petersen. In 1937 he joined the executive staff of the Verein and in 1951 became editor of the journals *Stahl und Eisen* and *Archiv für das Eisenhüttenwesen*.

In addition Dr. Thomas spent much time in research on the mechanism of the basic Bessemer process and a thesis on this subject brought him his degree of Dr.-Ing. from the Bergakademie Clausthal in 1930.

In 1954 he was appointed Director of Verein Deutscher Eisenhüttenleute and in the same year was made a Freeman of the Bergakademie Clausthal.

He has done much to bring about a close co-operation between science and industry and has served on many committees to that purpose. He is a member of the A.S.T.M., the Société Française de Métallurgie, The Iron and Steel Institute, The Institute of Metals, and Eisenhütte Oesterreich.

Bernhard Trautmann was born in 1901. He studied at the Technische Hochschulen of Berlin and Braunschweig and was awarded the degree of Dr.-Ing.

He was employed in the non-ferrous metal industry, for several years, and then devoted some time to research on nickel metallurgy. Later he became Technical Manager of the German Association of Zinc Rolling Mills. After the Second World War he was appointed Director of the Administration of the German Non-Ferrous Metal Industry. Since 1947 he has been working as an independent consulting metallurgist, in particular on new casting methods for the zinc industry.

Dr. Trautmann became Secretary of the Deutsche Gesellschaft für Metallkunde in 1953.

Pierre Marie Emile Olivier Ghislain Coheur was born at Herstal, Liège, in 1913. He studied at the University of Liège, obtaining his diploma as a metallurgical engineer in 1937, and submitting his Ph.D. thesis in Applied Science in 1942. He then spent some time studying physics and physical metallurgy at the University of Munich, the Technische Hoogeschool in Delft, and at the Carnegie Institute of Technology, Pittsburgh.

Until 1947, Professor Coheur's special interest lay in physical metallurgy, but since then he has studied more particularly problems related to steelmaking (steelplant, rolling mills, low-shaft furnaces, etc.). To gain more knowledge on these various problems he first spent two years (1943–44) in a Liège steelworks, and then visited

many educational and research centres and steelworks in Germany, Great Britain, Austria, Canada, the U.S.A., France, Holland, Italy, Luxembourg, Sweden, and Switzerland.

In 1939 Professor Coheur was appointed metallurgical assistant at the University of Liège ; four years later he became associated with the Fonds National de la Recherche Scientifique (National Foundation for Scientific Research), and in 1946 he was admitted to the Faculty of Applied Sciences at the University. In the following year he was appointed Professor. He has also been Director of the Liège Section of the Centre National de Recherches Métallurgiques (National Metallurgical Research Council) since its inception in 1906.

The author of many papers published in Belgian and foreign periodicals, Professor Coheur has lectured extensively in European countries and in Canada and the U.S.A. He has played an active part in the organization of various conferences, etc., including the International Research Conference in 1953, and is a member of various international research committees including the Joint Committee for Electron Microscopy, the International Committee on Flame Radiation, the International Steering Committee on Low-Shaft Furnaces, and the Technical Research Committee of the European Coal and Steel Community. He is also co-editor of the U.S. periodical *Acta Metallurgica*. In 1937 he was the winner of the Government Travel Bursary, and in 1952 he was awarded the Provincial Prize for the Encouragement of Industry. He is also an Officer of the Order of Merit of the Italian Republic.

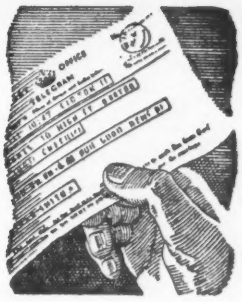
Sven Fornander was born at Hagfors, Sweden, in 1913. He received his technical education at the Royal Institute of Technology, Stockholm, graduating as a metallurgical engineer in 1939.

His first appointment was with the Swedish Institute for Metal Research, where he worked as research assistant under the late Dr. Gösta Phragmén. From 1941 to 1951 he was with Surahammars Bruks AB, first as Assistant Melting-Shop Manager, and later as Research Manager. He took up his present appointment as Director of Research of Jernkontoret in 1952.

Mr. Fornander is the author of several papers dealing with temperature measurement in the steel bath, theoretical and practical investigations on the basic open-hearth process, inductive stirring in arc furnaces, and the desulphurization of pig iron.

N E W S

Announcements and News of Science and Industry



THE IRON AND STEEL INSTITUTE

Special Meeting in Scunthorpe

As previously announced, a Special Meeting of The Iron and Steel Institute will be held in **Scunthorpe** from **Wednesday to Friday, 12th to 14th October, 1955,** by invitation of the Lincolnshire Iron and Steel Institute. The provisional programme of Technical Discussions and Works Visits was published in the May issue of the *Journal* (p. 66).

The Ladies' programme will include a visit to Lincoln. Ladies will be received in the Assembly Rooms by the Ladies Committee; a film of Lincoln Cathedral will be shown, and afterwards there will be a visit to the Cathedral itself. Ladies will be entertained to luncheon, and time will be available for further sightseeing.

A visit will also be paid to Normanby Park, Scunthorpe (by courtesy of Major E. C. R. Sheffield), to see this famous house and the beautiful gardens. The programme will include other interesting visits, and opportunities will be provided for visiting the iron and steelworks.

On the evening of Wednesday, 12th October, the Mayor and Corporation of Scunthorpe will entertain Members and Ladies to a Reception in Scunthorpe, and on Thursday, 13th October, they will be the guests of the Lincolnshire Ironmasters at a Ball at Elsham Hall, Brigg (by courtesy of Capt. J. G. G. P. Elwes).

A circular containing full information will be sent to all Members during the summer, and the complete programme will be published in a later issue of the *Journal*.

Autumn General Meeting, 1955

The **Autumn General Meeting** of The Iron and Steel Institute will be held on **Wednesday and Thursday, 16th and 17th November, 1955.** Full details of the programme will be given in a later issue of the *Journal*.

Annual General Meeting, 1956

Provisional arrangements have been made to hold the **Annual General Meeting** next year in London on **Wednesday and Thursday, 16th and 17th May, 1956.** The Members' Dinner will be held on the evening of Wednesday, 16th May.

Sir William Larke, K.B.E.

At the Annual General Meeting of the Institute, on Wednesday, 27th April, the retiring President, the Hon. R. G. Lyttelton, announced that the Council had nominated Sir William Larke, K.B.E. (Honorary Vice-President) to be an Honorary Member of the Institute in recognition of his eminent services to the steel industry.

The nomination had been made on the previous day, 26th April, 1955, which was the anniversary of Sir William's eightieth birthday.

Change on Council

Dr. MAURICE COOK has accepted an invitation to serve as an Honorary Member of Council during his term of office as President of The Institute of Metals, in succesion to Dr. S. F. Dorey, C.B.E., F.R.S.

NEWS OF MEMBERS

▶ Professor H. T. ANTELO has left Crisoldinié E. N., to become Head of the Technical Section of the Centro de Industriales Siderurgicos, Buenos Aires, Argentine.

▶ Mr. A. J. BLANCHARD has transferred from the North East Coast Laboratory of B.I.S.R.A., to the Sheffield Laboratories.

▶ Mr. KEITH BUTLER has been appointed Representative in the U.K. for The Broken Hill Proprietary Co., Ltd., Melbourne, Australia.

▶ Mr. ARTHUR CROSS has been appointed Assistant Superintendent of the Blast-Furnace Department of Empressa Siderurgia Pag. de Rio, Belencito, Colombia.

▶ Mr. J. HESLOP has been awarded the degree of Ph.D. of the University of Leeds for work on yielding and cleavage in steel.

▶ Mr. T. W. HOOD has left Samuel Fox and Co., Ltd., and has joined W. H. A. Robertson and Co., Ltd., Bedford.

▶ Mr. P. L. JACKSON has left the Ford Motor Co., Dearborn, Michigan, to become Research Metallurgist to the Misco Precision Casting Co., Whitehall, Michigan, U.S.A.

▶ Mr. ANDREW JOLLIE, General Manager of Steel, Peech, and Tozer, has been appointed Managing Director of Owen and Dyson Ltd.

▶ Mr. N. R. KRISHNASWAMY has returned to India from Germany, and has been appointed Works Manager of the Machine Tool Prototype Factory, Central Railway, Ambarnath, Bombay.

▶ Mr. F. V. LEWIS has joined Nu-way Heating Plants Ltd., Droitwich, Worcs.

▶ Mr. W. E. MAHIN has relinquished his appointment as Technical Director of the Vanadium Corporation of America, and has been appointed Vice-President and Director of Research of the Hunter Engineering Company, Riverside, California.

▶ Mr. R. S. M. MOFFATT has left the Appleby-Frodingham Steel Co., and has taken up the appointment of Metallurgist with Whessoe Ltd.

▶ Mr. F. C. PORTER has taken up an appointment as Corrosion Metallurgist with Avro Aircraft Ltd., Malton, near Toronto, Canada.

▶ Mr. K. ESBJÖRN SUNSTRÖM has been appointed Managing Director of Lundås Verkstäder AB, Häverödal, Sweden.

▶ Mr. G. BARRY THOMAS, formerly Director and General Manager of the Cargo Fleet Works of the South Durham

Steel and Iron Co., has been appointed General Works Manager of the Irlam Works of the Lancashire Steel Corporation.

Obituary

Mr. K. C. GARDNER, Chairman of United Engineering and Foundry Company, Pittsburgh, U.S.A., on 15th April, 1955, aged 78. Mr. Gardner and his Company were closely associated with the engineering design of Britain's strip mills in the new steelworks in Wales.

Mr. G. A. LOMAS, of A. C. Bamlett Ltd., Thirsk, on 10th April, 1955.

Capt. J. H. NEAD, of Chesterton, Indiana, U.S.A., on 13th September, 1954.

Mr. J. M. TOWLER, Joint Managing Director of Towler Bros. (Patents) Ltd., Leeds, on 6th April, 1955.

CONTRIBUTORS TO THE JOURNAL

A. P. Clark, B.Sc.—Design Engineer in the Plant Construction Department of Dorman Long (Steel) Ltd., Middlesbrough.

Mr. Clark was born in 1901, and graduated with Honours in Mechanical Engineering from the University of Manchester in 1921. After leaving the University, he joined the Appleby-Frodingham Steel Co., working first as Assistant Engineer in the Steel Works and subsequently as Assistant Chief Draughtsman. He took up his present appointment in 1946.

S. Cornforth—Design Engineer, Steel Furnaces, with Dorman Long (Steel) Ltd., Middlesbrough.

Mr. Cornforth was born in 1901 and was educated at Friends' School, Great Ayton, and at Middlesbrough High School. He joined the Redcar works of Dorman, Long and Co., Ltd., in 1916 as an engineering apprentice in the drawing office. In 1926 he left to join W. and M. Pumphrey Ltd., Thornaby-on-Tees, for work on the reconstruction of sugar mills. He returned to Dorman, Long and Co., Ltd., in the following year as a member of the engineering staff of the Britannia Works, and in 1931 he was transferred to the Central Engineering Department as Technical Assistant. On the incorporation of Bolckow Vaughan and Co., Ltd., he became Clerk of Works and Liaison Officer during the reconstruction and electrification of departments at the Cleveland Works. In 1933 he became Test Engineer in Charge of the main Test House at the Britannia Works ; in this position he was engaged on investigations into the properties of full-sized bridge girders and of riveted and welded constructions, and was also responsible for investigations into the development and manufacture of twisted and deformed steel for concrete reinforcement.

From 1937 Mr. Cornforth was given special opportunities for the study of open-hearth furnace design and operation in the five steelplants of the Company, and he was subsequently made responsible for steel furnace design. He took up his present appointment in 1951, and is at present engaged on project work in connection with soaking pits and reheating furnaces for new rolling-mill development.

William A. Haven, B.S., Met.E.—Formerly Vice-President and Director of Arthur G. McKee and Company, now retired.

Mr. Haven graduated in Chemical Engineering at Pennyslvania State College in 1909. He spent three years undergoing training in various operative posts with the Carnegie Steel Co., and from 1912 until 1917 held the position of Superintendent of Blast-Furnaces with several different companies. He then became General Superintendent of Northern Blast-Furnaces with the Republic Steel Corporation. In 1929 he joined Arthur G. McKee and Company as Vice-President and executive in charge of the Iron and Steel Division. During his 25 years with the Company, Mr. Haven played a prominent part in the design and construction of blast-furnaces and integrated iron and steelworks in various countries, including the Magnetogorski Works in Russia, the South Iron Works of the Appleby-Frodingham Steel Co., and plants at Volta Redonda in Brazil and Belencito in Colombia. He also spent considerable time in China and India as Consultant to the Kwangtung Provincial and National Governments, and as consultant to private firms and government agencies in the U.S.A., Mexico, Canada, and Italy. He retired from his appointment with Arthur G. McKee and Company in 1954.

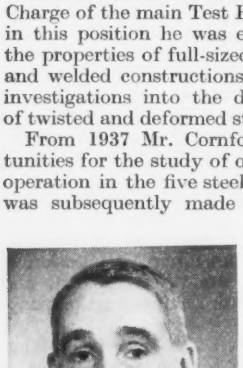
Mr. Haven holds a number of U.S. patents related to blast-furnace operation and equipment, and he developed the A.S.T.M. standard tumbler test for metallurgical coke. He is an emeritus member of the American Iron and Steel Institute, Past-Chairman of the Iron and Steel Division of the American Institute of Mining and Metallurgical Engineers, and Past-President of the Eastern States Blast Furnace and Coke Oven Association. He has been a member of The Iron and Steel Institute since 1938.

Nils Hellén—Assistant Manager of the Imatra Iron and Steel Works and legal adviser to Oy Vuoksenniska AB, Finland.

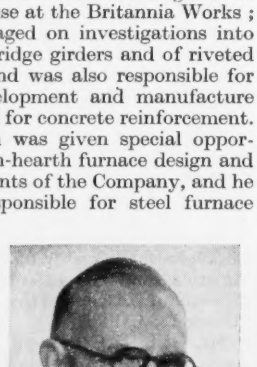
Mr. Hellén was born at Wiborg, Finland, in 1914, and matriculated at the University of Helsingfors in 1932. He studied at the Universities of London, Heidelberg, and Munich, and was awarded the degree of Mag. Phil. (Modern Languages) in 1936 and that of Candidate of Laws in 1942. In 1948 he qualified for the office of a judge.

Mr. Hellén served in the Exchequer of Finland from 1940 until 1945, first as Chief Accountant and later as a Director. He then took up his present appointment with Oy Vuoksenniska AB.

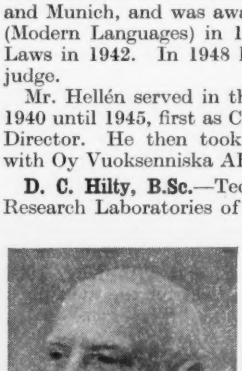
D. C. Hilty, B.Sc.—Technical Advisor in the Metals Research Laboratories of the Electro Metallurgical Co.,



A. P. Clark



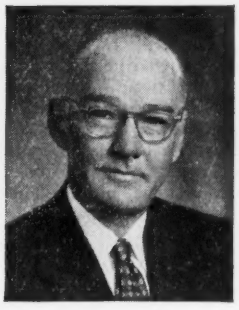
S. Cornforth



W. A. Haven

N. Hellén

D. C. Hilty



H. P. Rassbach

C. E. A. Shanahan

R. Wilcock

a Division of Union Carbide and Carbon Corporation, Niagara Falls, N.Y., U.S.A.

Mr. Hilty graduated with highest honours in Electrochemical Engineering from the Pennsylvania State University in 1935. His first employment was as a metallurgist at the Vandergrift, Pa., plant of the United States Steel Co. During the Second World War he saw active service as an officer in the Corps of Engineers of the U.S. Army, and in 1943 he joined the Metals Research Laboratories, which were then known as the Union Carbide and Carbon Research Laboratories, Inc. He took up his present appointment in 1953.

The author of many papers, Mr. Hilty has been concerned mainly with the physical chemistry of steelmaking, particularly in connection with deoxidation, the mechanism of inclusion formation, and reactions in stainless steel melting. The co-recipient with Mr. W. Crafts of the F. L. Toy Award in 1953, he is a member of the Physical Chemistry of Steelmaking Committee of the American Institute of Mining and Metallurgical Engineers.

H. P. Rassbach, B.Sc.—Assistant Manager, Technical Service and Development, to the Electro Metallurgical Co., a Division of Union Carbide and Carbon Corporation.

Mr. Rassbach graduated in Metallurgical Engineering from the Carnegie Institute of Technology in 1925. He then became associated for a number of years with the Midvale Co., Philadelphia, where he was concerned with open-hearth and electric furnace melting and the forging of a wide variety of alloy steels. He has had practical experience of stainless-steel melting since the time when this process was in the pioneering stage. He became associated with the development group of the Electro Metallurgical Co. five years ago, and has since played an active part in programmes designed to improve stainless-steel melting processes.

Mr. Rassbach is the author of a number of papers on melting practices for heavy forging steel and stainless steel.

C. E. A. Shanahan, B.Sc., F.R.I.C.,* A.I.M.—Chief Chemist at the R.T.S.C. Laboratories, Whitchurch.

Mr. Shanahan served a five-year indentured apprenticeship with the British Thomson-Houston Co., Ltd., and in 1940 he was awarded an external Honours degree in Chemistry of London University. From 1940 until 1948 he worked in the Research Laboratories of the British Thomson-Houston Co., Ltd., studying physico-chemical problems associated with lamp manufacture, cemented carbides, and plastics. During this time he became a part-time lecturer in mathematics and physical chemistry at Rugby College of Technology and Arts. He then joined the British Iron and Steel Research Association, where he was later appointed Principal Scientific Officer in charge of process chemistry research in the Steelmaking Division. He took up his present post in 1954.

R. Wilcock—Works Metallurgist to Samuel Fox and Co., Ltd., Stocksbridge.

Mr. Wilcock was educated at the Almondbury Grammar School. He joined the Research Department of Samuel Fox and Co., Ltd., in 1934, and took up his present appointment in 1948. He obtained his Associateship in Metallurgy at the University of Sheffield in 1939.

A. W. W. Watson—Head of the Labour and Training Department of the British Iron and Steel Federation.

Mr. Watson was born in 1917, and was educated at Highgate School and St. Edmund Hall, Oxford, graduating with 2nd Class Honours from the School of Jurisprudence. He joined the British Iron and Steel Federation in 1938. From 1939 until 1946 he served with the Gordon Highlanders and the Royal Artillery, and then rejoined the Federation. He held the appointment of Personal Assistant to the Commercial and Technical Director until 1947 when he joined the Labour Department. He took up his present appointment in 1952.

Mr. Watson represents the Training Committee on the Federation's Education Committee, and is a member of the B.E.C. Council.

AFFILIATED LOCAL SOCIETIES

Sheffield Metallurgical Association

It has been agreed that an application for affiliation to The Iron and Steel Institute from the Sheffield Metallurgical Association shall be accepted. Normally, it is a condition of affiliation that only one society in a district shall be affiliated, but the Sheffield Society of Engineers and Metallurgists has agreed to the proposal, provided that steps are taken to reduce the risk of financial loss arising from the affiliation of the Sheffield Metallurgical Association.

INSTITUTE OF METALS

Students' Essay Competition, 1954

The Adjudicators have awarded a first and a second prize in connection with the 1954 Students' Essay Competition, as follows :

First Prize of 25 guineas to Dr. A. P. Miodownik, B.Sc., L.I.M. (Battersea College of Technology), for an essay on "*The Significance of Microhardness Testing.*" On the recommendation of the Adjudicators, the essay will be published in the Institute's *Bulletin*.

Second Prize of 15 guineas to Mr. Surindar Singh (County Technical College, Wednesbury), for an essay on "*The Kirkendall Effect.*"

Particulars of the 1955 Students' Essay Competition will be published in due course.

NEWS OF SCIENCE AND INDUSTRY

British Coal Utilization Research Association

The British Coal Utilization Research Association will hold Open Days on **8th, 9th, and 10th June, 1955,** when

the work of the laboratories at Leatherhead will be available for inspection by visitors. Wednesday, 8th June, will be reserved for Members and their friends, and in order to bring the activities of the Research Association to a wider audience the open period will be extended for a further two days. On 9th and 10th June, the laboratories will be open to visitors from professional organizations, public authorities, other Research Associations, schools, and other bodies likely to be interested.

A wide range of exhibits is being prepared to show the scope of the research programme on coal utilization that is now being carried out at Leatherhead.

Société de l'Industrie Minérale Congress in St.-Étienne and Paris

To commemorate the centenary of its foundation, the Société de l'Industrie Minérale is to hold an international congress in St.-Étienne from **16th to 18th June** and in Paris from **18th June to 3rd July, 1955.** The programme will include a session on iron and steel, comprising blast-furnaces, steelworks, rolling mills, and utilization of heat. An international exhibition of the mining industry will be held in Paris from 18th June to 3rd July, and will display up-to-date equipment, models of metallurgical and mining works and installations, etc. The address of the General Secretariat of the Congress is 60 Boulevard St.-Michel, Paris, 6.

Powder Metallurgy Congress in Austria

The second International Powder Metallurgy Congress will take place in Reutte, Tyrol, Austria, from **20th to 23rd June, 1955.** The subject of the Congress, which is sponsored by Dr. P. Schwarzkopf, President of the American Electro Metal Corporation, will be "*High Temperature and Corrosion-Resistant Materials by Powder Metallurgy.*" About 300 representatives from 17 nations will attend, including over 30 scientists, industrialists, and engineers from the U.K. The dates of the Congress were chosen to make it possible for participants in the Joint Metallurgical Societies' Meeting in Europe to attend.

Iron Through the Ages—French Meeting

An international meeting on "*Le Fer à Travers les Âges : Hommes et Techniques*" will be held in Nancy, France, on **3rd–6th October, 1955.** The scope of the meeting will cover the history of ironmaking techniques, industrial and commercial organization, and the effects of the growth of industry on industrial communities. An exhibition illustrating the evolution of ironmaking from prehistoric times to the present day will be held in conjunction with the meeting, which will include visits to metallurgical plants in the Lorraine region.

Communications should be addressed to the Secrétariat du Colloque International, Musée Lorraine, Palais Ducal, Nancy.

Congress on Industrial Chemistry—Madrid

The twenty-eighth International Congress on Industrial Chemistry will be held in Madrid on **23rd–31st October, 1955.** It will be organized by the Société de Chimie Industrielle, and the programme will include visits to industrial regions of Spain.

Société Française de Métallurgie

Monsieur Raoul de Vitry, Vice-President and Directeur-Général of the Compagnie Pechiney, has been elected President of the Société Française de Métallurgie for 1955, in succession to Monsieur E. Dupuy, who now becomes Secretary-General of the Society.

Reorganization of EFCO Group

The EFCO Group of Companies has recently been reorganized in the form of a holding company and four subsidiaries. The holding company is to be known as EFCO Ltd., and will provide general administrative services for the other Companies of the Group. Electric Furnace Co., Ltd., will become a subsidiary, but will continue to design and manufacture the same range of products as before. The remaining subsidiaries, Electric Resistance Furnace Co., Ltd., Electro-Chemical Engineering Co., Ltd., and EFCO-Industrieofen A.G., will not be affected by the reorganization.

New Non-Destructive Examination Society

A Society of Non-Destructive Examination has recently been formed in Great Britain to promote the use of non-destructive testing methods. It has always been a disadvantage of many engineering test methods that the specimen is severely damaged or destroyed during the tests. However, radiographic, magnetic, acoustic, ultrasonic, and other methods of non-destructive testing can be applied if desired to the whole output of any particular manufacturing process, and an overall improvement in the testing efficiency is thus effected.

The new Society will help to popularize the use of these methods by encouraging the free interchange of information between designers and users on all the associated techniques that have evolved in recent years. The membership of the Society will include persons from the aircraft, shipbuilding, electrical, transport, and other industries, and from atomic energy research departments. Further information on the activities of the Society can be obtained from the headquarters at Duncan House, Dolphin Square, London, S.W.1. The Honorary Secretary is Mr. C. C. Bates.

Film on Industrial Engineering

A new film, "*Planned for the Purpose*", produced by the Electrical Development Association, deals with some of the important aspects of industrial engineering, and is intended for directors, managers, industrial engineers, and others concerned with increasing productivity. It covers the planning of new projects, plant siting and layout, building design, and various industrial techniques including materials processing and handling. Copies of the film (running time 43 min.) are available in 16-mm. and 35-mm. sizes on free loan from the Association at 2 Savoy Hill, London, W.C.2.

Argonaut Welding

The development of the automatic consumable-electrode argon-arc welding process and its applications are demonstrated in a new film "*The Argonaut Welding Process,*" produced for the British Oxygen Co., Ltd.

This colour film illustrates the development of the process and shows examples of its application to the welding of aluminium, stainless steel, copper, and mild steel. A number of high-speed photographs are included showing the characteristics of the arc and the method of droplet metal transfer in different welding positions. The effects of nitrogen as a shielding gas can also be compared with those of argon.

The film is a 16-mm. Kodachrome (sound) with a running time of 26 min. Copies are available on loan under the usual conditions and application should be made to the Company.

Steel Structures Painting

The second of two volumes of the "*Steel Structures Painting Manual*" has recently been published by the

Steel Structures Painting Council. The new volume, entitled "*Systems and Specifications*," contains specific recommendations on painting a large variety of steel structures and surfaces in various exposures, and also incorporates comprehensive guides and indexes. The book consists of 300 pages and is bound in leatherette with hard covers. Copies may be ordered from the Council at 4400 Fifth Avenue, Pittsburgh, 13, Pa., U.S.A., price $5 each, post free.

Petroleum Equipment

The 1955–56 edition of "*British Petroleum Equipment*" has recently been published and is a composite catalogue of oilfield equipment manufactured in Great Britain. It is produced by the Council of British Manufacturers of Petroleum Equipment, and copies are available from the Council's offices at 79 Buckingham Palace Road, London, S.W.1, price £2 10*s.* 0*d.* each.

Handling of Materials

The latest in the Action Pamphlet Series published by the British Productivity Council is entitled "*The Handling of Materials.*" The pamphlet sets out the advantages to be gained from good handling practices, and outlines the principles to be followed. Particular stress is laid on the desirability of studying any job to reduce handling to a minimum before mechanization. A section is included on the application of the main principles; both the technical and human aspects of dealing with handling problems are discussed.

Copies of the pamphlet, No. 3 in the Series, are available from the Council at 21 Tothill Street, London, S.W.1, price 9*d.*

Refractory Chart

A revolving refractory chart that has recently been produced is intended to aid manufacturers of refractories in their choice of materials, aggregates, etc., for various purposes. The chart gives various uses for refractory concrete, aggregates, suggested mixes, and the hot-face temperatures that such mixtures should be capable of withstanding. Copies of the chart may be obtained, free of charge, from the Lafarge Aluminous Cement Co., Ltd., 73 Brook Street, London, W.1.

Change of Address

The BUTTERLEY CO., LTD., has removed to new premises at 9 Upper Belgrave Street, London, S.W.1. (Tel. Sloane 8172–3 and 9106–7).

Industrial Publications Received

▶ Handbook on induction heating produced by Radio Heaters Ltd., gives details of applications of the process to crankshaft hardening, soldering and brazing, through heating, annealing, heating of carbon, etc.

▶ Brochure giving details of Klonne-type dry gasholders —Publication No. KG 1054—Ashmore, Benson, Pease and Co.

▶ Brochure on the manufacture of H_2SO_4 from sulphide ores by the contact process—Publication No. SAC 354—Power-Gas Corporation Ltd.

▶ Brochure on the 'Favorit' filter process for the recovery of dust and fumes—Publication No. FF 355—Power-Gas Corporation Ltd.

▶ "*Review of the Year* 1954," the statement of the Chairman of Associated Electrical Industries Ltd., is a 56-page illustrated booklet giving details of the work and policy of A.E.I.

▶ Brochure on foundry plant, giving details of cupolas, various types of chargers, crucible furnaces, etc.—Publication No. V.9A (replacing No. V.9)—Incandescent Heat Co., Ltd.

▶ Brochure on the repair and joining of aluminium casting alloys by 'Thesscal' hard solders—Publication No. HA 2/155: on aluminium hard soldering with 'Thesscal A' solder and flux—Publication No. HA 1/155: Sheffield Smelting Co., Ltd. The Company has also published an illustrated booklet, "*Metals in the Service of Man,*" which gives details of the activities and products of the Company.

▶ Brochure on the application of the powder-metallurgy process to the production of wrought nickel and nickel alloys contains an illustrated description of the manufacturing process, together with tables comparing properties of materials produced by powder metallurgy with those of alloys produced by conventional methods of melting—Henry Wiggin and Co., Ltd.

▶ Leaflet describing the 'Brightray' series of electrical resistance materials, and containing brief notes on the type of service for which each grade is intended—Henry Wiggin and Co., Ltd.

CORRIGENDUM

A Note on Hairline Cracking

In the synopsis of the paper by D. R. Wood, published in the April, 1955, issue of the *Journal*, p. 317, the words "... carried out on castings of Inconel (Ni-Cr-Fe alloy) ..." should be deleted.

DIARY

1st–18th June—Joint Metallurgical Societies Meeting in Europe—London, Düsseldorf, Liège, Paris.
Mechanical Engineers)—Conference on Combustion —Boston, Mass., U.S.A.

20th June–2nd July—INSTITUTO DEL HIERRO Y DEL ACERO—Third General Assembly.

16th June–3rd July—SOCIÉTÉ DE L'INDUSTRIE MINÉRALE —International Centenary Congress—St.-Étienne and Paris.

20th–23rd June—Second International Powder Metallurgy Congress—Reutte, Tyrol, Austria.

21st June—CLEVELAND INSTITUTION OF ENGINEERS—Works visit to the Workington Iron and Steel Works.

21st–24th June—GROUPEMENT POUR L'AVANCEMENT DES MÉTHODES SPECTROGRAPHIQUES—18th Congress—9 Avenue d'Iéna, Paris.

22nd–25th June—INSTITUTE OF PHYSICS (Non-Destructive Testing Group)—Summer Meeting—Societies' Room, Royal Technical College, Glasgow.

26th June–1st July—AMERICAN SOCIETY FOR TESTING MATERIALS—58th Annual Meeting—Atlantic City, U.S.A.

28th June–9th July—British Instrument Industries Exhibition—Earls Court, London.

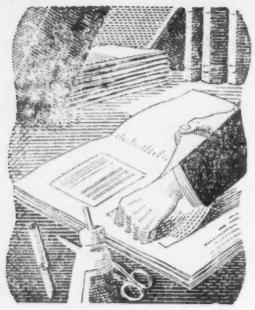
TRANSLATION SERVICE

(The previous announcement was made in the May, 1955, issue of the *Journal*, p. 69.)

TRANSLATION AVAILABLE

No. 500 (German). E. PFLAUME and F. BAUER: "Technical Investigation of the Operation of a Forge." (*Die Technik*, 1954, vol. 9, Mar., pp. 152–156).

CHARGES FOR COPIES OF TRANSLATIONS—The charge for translations is £1 for the first copy and 10*s.* for each additional copy of the same translation. Requests should be accompanied by a remittance. These translations are not available on loan from the Joint Library.



ABSTRACTS OF CURRENT LITERATURE AND BOOK NOTICES

Iron and Steel Manufacture and Related Subjects

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MINERAL RESOURCES

The Geological Basis of the Oolithic Iron Ores of the Mining Basin of Luxembourg. M. Lucius. (*Rev. Tech. Luxembourg*, 1954, **46**, Oct.-Dec., 223–241).

Sweden's Iron Ore. T. L. Joseph. (*Blast Furn. Steel Plant*, 1954, **42**, Nov., 1281–1291). The occurrence and analysis of iron ores in Sweden are considered first. The Wiberg-Söderfors sponge iron process, as operated in Sweden, is described together with a brief note on American sponge iron production. The manufacture of iron powder in Sweden and in the U.S.A. is also described.—B. G. B.

Mineral Resources of South-West Africa. L. G. Paine and P. T. Wilson. (*Min. Mag.*, 1954, **91**, Dec., 329–335). A brief but comprehensive review is given of the mineral resources, in which overseas mining concerns are taking increasing interest. The area contains great reserves of low-grade iron ores, some difficult-to-win high grade manganiferous iron ores, an ore at Eisenberg used for a long time as flux in lead-copper smelting, and small deposits of high-grade magnetite.—K. E .J.

ORES—MINING AND TREATMENT

Electric Rotary Drilling : Development in Iron Ore Mining. E. W. Hurd. (*Iron Coal Trades Rev.*, 1954, **169**, Nov. 12, 1155–1158 : *Colliery Guardian*, 1954, **189**, Nov. 11, 619–624). Details are given of an electric rotary drilling unit in use at the Dragonby ironstone mine in the Scunthorpe area. It combines high drilling efficiency and safety to the operator without fatigue.—G. F.

The Steep Rock Iron Ore Development. C. J. Poppe. (*Blast Furn. Steel Plant*, 1954, **42**, Dec., 1425–1427). A short account is given of the drainage and subsequent mining of iron ore from the bottom of Steep Rock Lake in N.W. Ontario. The projected output from the area is 10,000,000 tons of high grade ore per year.—B. G. B.

The Cerro Bolivar Iron Mine (Venezuela). (*Echo Mines*, 1954, Nov., 745–749). An illustrated account of the occurrence and development of this ore deposit is presented. The ore is a mixed hematite and limonite with occasional amounts of magnetite. The dry ore contains 63·5% Fe, and as mined 58% Fe. Details of the methods of mining, crushing, and transporting the ore are given. The projected output is 5,000,000 tons/year of ore. Two million tons of ore are expected to be produced in 1954.—B. G. B.

Ore Handling and Crushing System for Orinoco Mining Co., Puerto Ordaz, Venezuela. L. O. Millard. (*Amer. Soc. Civ. Eng. : Mines Mag.*, 1954, **44**, July, 30–34). An illustrated account is given of the installation at Puerto Ordaz, which is essentially a transfer station where Cerro Bolivar iron ore is unloaded from rail, crushed, stored, reclaimed, and loaded into ocean-going ships. The plant, designed to handle all varieties of ore including sticky types, is rated at 6000 tons/hr., and the ship-loading equipment has a peak capacity of 12,000 tons/hr., with flexibility to meet a 40-ft. tidal variation.—K. E. J.

The Sept-Iles Ore Terminal. (*Brit. Eng.*, 1955, **37**, Jan., 240–244). An account is given of the engineering projects undertaken for the exploitation of iron ore at Schefferville (Knob Lake) in Quebec-Labrador. At Sept-Iles ore is blended and crushed, and can be stockpiled (from two stacker units) or loaded to carrier ships at a maximum rate of 8000 tons/hr. For smooth operation of the conveyor system Vulcan-Sinclair scoop-control fluid couplings, made by Fluidrive Engineering Co. Ltd., and B.T.H. squirrel-cage motors are used ; the conveyor reaches maximum speed smoothly in 45 sec. and can be " inched."—K. E. J.

The Role of Iron-Ore Beneficiation. The Solution of the Taconite Problem in the U.S.A. W. A. Haven. (*J. Iron Steel Inst.*, 1955, **180**, June, 144–154). [This issue].

Impact Crushing. Spies. (*Colliery Guardian*, 1954, **189**, Sept. 23, 382–383). In Nov., 1950, a new kind of crushing and preparation machine, the Hazemag Impeller Breaker, was introduced at the Friedrich Thyssen 2/5 Mine, Duisburg-Hamborn. The feed is caught by a rapidly rotating and horizontally pivoted rotor, by which it is thrown against impact blades mounted within the machine casing. The theory of impact crushing is briefly explained. Parts subject to wear are easily and cheaply replaced. Results of trials on various materials encountered in coal mining are quoted.

The Gutehoffnungshütte Pan Sintering Process. (*Blast Furn. Steel Plant*, 1954, **42**, Dec., 1420–1424). This process employs square pans which are transported by a special travelling crane. The sintering equipment comprising pans, roller table, pan dumping machine, charging equipment, combustion stands, and ignition car are arranged in line. The process is suitable for producing 100–3000 tons/day of sinter. The advantages of the process are explained.—B. G. B.

Down-Draught Pelletizing Is Chosen for Reserve's Taconite Project. (*Eng. Min. J.*, 1954, **155**, Oct., 96–98). **New Process for Heat Hardening Taconite Pellets.** (*Blast Furn. Steel Plant*, 1954, **42**, Nov., 1299–1303). **Reserve's E. W. Davis Works Installs New Heat Hardening Process for Taconites.**

(*Min. Eng.*, 1954, **6**, Oct., 974–975). The successful development of a new process for heat hardening of pellets of taconite concentrates is announced by A. G. McKee & Co. and Allis-Chalmers Manufacturing Co. The plant, for the Reserve Mining Co., will produce 12,000 tons of pellets per day ; it is a horizontal travelling grate process operating at 2300–2400°F. Easy quality control, minimum breakage and operating simplicity are special features.—K. E. J.

Contribution to the Study of the Distribution of the Elements in Lorraine Iron Ores. G. Turpin. (*Publ. Inst. Rech. Sid.*, Series **A**, 1952, (42), July, 1–65). Investigations on the form in which various elements and groups are present in the ores are reported. PO_4^{4-}, the halogens, CO_2, and sulphur are included in the studies.—T. E. D.

Grinding Practice as Related to the Characteristics of Materials to be Pulverised. R. North. (*Trans. Inst. Chem. Eng.*, 1954, **32**, (1), 54–60). The properties of materials as they affect the design of grinding equipment are enumerated and discussed.—T. E. D.

Metallurgical Tests on Scappoose (Oregon) Iron Ore. J. P. Walsted. (*U.S. Bur. Mines, Rep. Invest.* 5079, 1954, Oct.). The results of ore dressing tests carried out on this low grade ore and smelting trials in a cupola and electric furnace are given. Pig iron made from the raw ore contains 1·25 to 1·49% phosphorus. The phosphorus content of the ore can be reduced by roasting with sodium carbonate followed by leaching with water.—B. G. B.

Adsorption of Electrolytes on Finely Pulverized Minerals. Conductometric Studies. G. G. Bring. (*Jernkontorets Ann.*, 1954, **138**, (11), 671–701). [In Swedish]. The adsorption of electrolyte on crushed quartz, silicates, oxides of iron, and apatite and sulphide ores was studied, the electrolytes being acids, alkalis, and dilute metal salt solutions. The specific conductance of the solutions was measured before and after treatment and, in the case of acids or strong alkalis, this was lower in the residual than in the original solution, due to adsorption by the mineral. The curves plotted make it possible to determine the concentrations at which adsorption still takes place and, to some extent, the adsorbed quantities. G. G. K.

The Orcarb Process for Preparing Iron Ore Concentrates for Smelting in the Electric Furnace. C. E. Lesher. (*Tidsskr. Kjemi, Bergvesen Met.*, 1954, **14**, Nov., 159–165). [In English]. Iron ore preheated to 593° C. and finely divided coking coal are fed to a mixing conveyor and then to a retort, a rotary steel cylinder externally heated. Tar vapour is condensed and used for process heat. The bituminous matter from the coal coats the ore fines and the tumbling action results in the production of small aggregates consisting of coke coated with ore. This material (called Orcarb) having carbon contents from 12–25% is delivered to the electric furnace at 950° F. Operating data are given for an American pilot plant having a capacity of 675 kg./hr., with details of tests on taconite and hematite concentrates.—G. G. K.

Magnetic Roasting Tests on French Iron Ores. P. Emery and J. Givaudon. (*Pub. Inst. Rech. Sid.*, Series **A**, 1953, (60), Oct.). In the first section, magnetic roasting tests, performed by IRSID, are described, with details of the apparatus. Two ores were studied, a low-grade siliceous Micheville ore, and an ore from Mont-Saint-Martin. The second section deals with tests on the Mont-Saint-Martin ore carried out by the Société Activat, with details of furnace and methods. The third section is concerned with fluidization phenomena examined during the above studies. Full results are given. Magnetic separation of the roasted ores is described with diagrams in the appendix.—T. E. D.

Industrial Trials on Enrichment by High Intensity Magnetic Separation of a Lorraine Iron Ore at Kahlenberg (Germany). L. Coche. (*Bull. Tech. des Mines de Fer*, 1953, (31): *Publ. Inst. Rech. Sid.*, Série **A**, 1953, (58), July). The installations at Kahlenberg are described with diagrams illustrating the crushing, screening, and drying scheme, the enrichment scheme, the magnetic separator, and the layout of the Kahlenberg works. Enrichment tests performed on Mont-Saint-Martin fines are described and results given.—T. E. D.

Research in Iron-Making. Study of Upgrading and Agglomeration of Ores, and Chemistry of the Blast-Furnace Operation. E. W. Voice. (*Metal Treatment and Drop Forg.*, 1954, **21**, Nov., 534, 533). The functions, facilities and main fields of work of the Iron Making Division of B.I.S.R.A. are outlined.—P. M. C.

Agglomeration of Fine Ores. E. W. Voice and R. Wild. (*Metal Treatment and Drop Forg.*, 1954, **21**, Nov., 535, 536, 533). Agglomeration of fine iron ores, which are available in large quantities from West Africa, is very important and this problem is being studied by the Iron Making Division of B.I.S.R.A. A brief survey is presented of the work being done on the nature and mechanism of the agglomeration process using sintering techniques.—P. M. C.

Substituted Starches in Amine Flotation of Iron Ore. C. S. Chang. (*Min. Eng.*, 1954, **6**, Sept., 922–934). The replacement of active groups in corn starch causes varying effectiveness as an iron oxide depressant in amine flotation of iron ore, usually impairing its value. Increased ability to depress iron oxides is generally accompanied by a similar ability concerning quartz. Starches are assessed in the following order of decreasing ability to depress iron oxides : aminoethyl starch, starch phosphate, starch pearl, starch sulphonate, starch xanthate, oxidized starch.—K. E. J.

How Sheffield's Beneficiation Plant Upgrades Texas Iron Ores. C. L. Lloyd, jun. (*Eng. Min. J.*, 1954, **155**, Nov., 98–100). At the Rusk, Texas, plant of Sheffield Steel, the local crumbly clayey ore (Fe content between 17 and 45%) is concentrated by crushing, classifying and hand-picking to a product averaging 45% Fe.—K. E. J.

Instrumentation for Continuous Quality Control of Sinter. E. H. Rose and D. J. Reed. (*Amer. Inst. Min. Met. Eng., Blast Furnace and Raw Materials Conf.*, Apr., 1954 : *Indust. Heating*, 1954, **21**, July, 1333–1334). The use of a recording magnetic permeability meter which gives an indication of the strength of a sinter and a recording pyrometer on the exit side of the ignition zone are very briefly discussed.—A. D. H.

Removal of Sulphur during Iron-Ore Sintering. Part I—Laboratory Studies of the Kinetics of Sulphide and Sulphate Decomposition. V. Giedroyc. (*J. Iron Steel Inst.*, 1955, **180**, June, 129–139). [This issue].

New Plant Successfully Floats Michigan Jasper. R. Cochran. (*Eng. Min. J.*, 1954, **155**, Aug., 100–104, 108). Details are given of operations at the Humboldt Mining Co., now in the commercial stage. Jasper ore from the Lake Superior region (similar to taconite) of iron content 34% is concentrated to 61–63% by flotation ; the 1954 output is 175,000 tons of concentrate. Of special interest is the use of a Linde jet-piercing rig for blast hole work.—K. E. J.

High-Capacity Magnetic Filter Treats Magnetic Concentrates. B. G. Fagerberg. (*Eng. Min. J.*, 1954, **155**, Oct., 77–79). As part of the modernization programme by the Luossavaara-Kiirunavaara Co., at their works in Malmberget, Sweden, the dewatering of wet magnetic concentrates in shaking tanks has been replaced by magnetic filters, essentially vacuum drum filters equipped with magnetic racks. These operate on concentrates of a wide range of water content, and are simple and low in maintenance costs. Running with some overflow removes the finer gangue particles.—K. E. J.

FUEL—PREPARATION, PROPERTIES, AND USES

Atomization of Liquid Fuels by High Pressure Natural Gas. G. Grosvenor. (*Iron Steel Eng.*, 1954, **31**, Oct., 77–80). After a brief description of the mechanics and chemistry of liquid fuel flames, the author describes the burner developed by the Colorado Fuel and Iron Corp. which atomizes liquid fuels with high-pressure natural gas. It is claimed that this burner is especially valuable in a shop with a high scrap charge.—M. D. J. B.

Temperature Dependence of Stability Limits of Burner Flames. J. Grumer and Margaret E. Harris. (*Indust. Eng. Chem.*, 1954, **46**, Nov., 2424–2430). The effect of the initial temperature of unburned gas on flame stabilization is described in relation to the performance of fuels on gas burners. Flash-back and blow-off characteristics were measured. Critical boundary velocity gradients were calculated both at room temperature and at burner temperature, and the relation between the two established. Experiments were carried out with the flames of methane and propane only, but are considered to be applicable to all flames.—G. E. D.

Contribution to the Graphical Solution of Transient Heat Conduction Problems, Using the Method of Finite Differences. H. D. Baehr. (*Forsch. Ingenieurwesens*, 1954, **20**, No. (1), 16–19). Transient heat conduction problems in cylinders and spheres, including solids composed of layers with different thermal properties, are treated graphically by the method of finite differences.—H. R. M.

The General Law of Heat Transmission for Turbulent Flow in Pipes, and the Meaning of the Dimensionless Numbers. E. Hofman. (*Forsch. Ingenieurwesens*, 1954, **20**, (3), 81–93). By using an experimentally confirmed velocity distribution, a practical form of the dimensionless Prandtl heat transmission formula is developed. It is compared with test results and the formulæ of other investigators.—H. R. M.

Fuel Economy in Materials Handling. R. Solt. (*Engineer*, 1954, **198**, Nov. 12, 661–662). The author surveys common practices and gives comparative data on the use of fuel in transport and handling systems. Reference is made to the amount of handling which takes place in steelworks and it is suggested that fuel economics could be achieved by good maintenance and by efficient operation and control of the existing facilities.—M. D. J. B.

Fuel Balance at Steubenville Works Controlled by Utilizing Summarizers. J. H. Dickson and G. C. Nuzum. (*J. Met.*, 1954, **6**, Oct., 1127–1129). The authors outline the fuel requirements of the Steubenville Works of Wheeling Steel Co., and discuss the supply systems of the three available fuels, coke-oven gas, fuel tar, and fuel oil. In the open-hearth plant, the various fuels can be controlled individually or in combination by the use of a summarizer based on total heat input.—G. F.

Steam Raising in Steelworks : Use of Waste-heat Boilers. A. E. Williams. (*Iron Steel*, 1954, **27**, Dec., 572–576). The author discusses the prominent part played by the waste-heat boiler in the conservation of fuel in steelworks, presents illustrations of the quantity of heat available for the generation of steam, and shows the economies which can be effected. The design and operation of different types of boiler are described. Further improvements should be directed towards smaller and more compact plants with a higher yield of steam or power per unit of original furnace fuel.—G. F.

Partial Insulation of Idle Coke Ovens. J. R. Purdy. (*Blast Furn. Steel Plant*, 1954, **42**, Dec., 1405–1412). Experiences at the Pueblo plant of the Colorado Fuel and Iron Corp., U.S.A., on maintaining coke-oven batteries hot whilst not in use are described. The methods for insulating the oven doors and charging holes are explained and resulted in a 50% reduction in maintenance costs. The complete shutting down of ovens is not recommended.—B. G. B.

The Rapid Carbonization of Coal. R. A. Kirby. (*Brit. Coal Utilization Res. Assoc. Monthly Bull.*, 1954, **18**, June, 241–259). The literature is reviewed. (79 references).

A Steelworks Producer Gas Plant. (*Coke Gas*, 1954, **16**, Oct., 404–407). The predistillation-type gas producer and cleaning plant at the works of the English Steel Corporation Ltd., Sheffield, is described. The coal distillation takes place in a retort immediately over the section where the residual coke is gasified. The layout of the producer and gas cleaning plant is shown diagrammatically, and the automatic method of charging the producer is described. The instrumentation is mentioned briefly.—T. E. D.

Fuel Technology in the Iron and Steel Industry. L. H. W. Savage. (*Metal Treatment and Drop Forg.*, 1954, **21**, Nov., 495–498, 502). A review is presented of the fields of activity of the fuel section of the physics department of B.I.S.R.A. Recent and current work is described which includes studies of ingot heat conservation (casting bay and soaking pit practice), flame control, flame radiation, gas cleaning, and temperature distributions in furnace foundations.—P. M. C.

Fuel Economy in Iron and Steel Works: Integrated and Non-Integrated Plants Compared. W. F. Cartwright and J. T. Davies. (*Iron Coal Trades Rev.*, 1955, **170**, Jan. 14, 79–83). In comparing fuel economy in integrated and non-integrated works producing tinplate and sheet, the authors assume that production is complete in the former whilst the latter is considered as five separated works, namely, coal washery, and coking plant, blast-furnace, cold metal shop and slabbing mill, hot-strip mill, and tinplate and cold-reduced sheet mill. Statistical figures for fuel consumption are presented and thermal balances for both the integrated and non-integrated plants are compared. The advantage of integration appears greatest when the commercial value of the heat used is taken as the basis of comparison.—G. F.

Similarity Theory for Radiation in Furnaces. C. H. Yhland. (*Tekn. Tidskr.*, 1954, **84**, Nov. 16, 1006). [In Swedish]. The author's theory (that each measured quantity stated in a suitable dimensionless form must be a function of the dimensionless coefficients which determine radiation conditions) is applied to the tests, on lines parallel with those of the International Committee on Flame Research, undertaken in Stockholm. Extracts from the results show total heat transfer and flue gas temperature as functions of these coefficients.—G. G. K.

Investigation of Flame Radiation in Oil Firing. B. McHugh. (*Tekn. Tidskr.*, 1954, **84**, Nov. 16, 1001–1006). [In Swedish]. A detailed account of the tests conducted in Stockholm on lines parallel with those of the International Committee on Flame Research deals with test equipment, flame stability, radiation measurement, reproducibility, test planning and results, preheating, and influence of the method of atomizing.—G. G. K.

Calculation of Heat-Exchanger Performance. O. Seibert. (*BWK*, 1954, **6**, Nov., 417–419). A graphical method, based on nomograms, facilitating the determination of the most frequently required parameters in heat-exchange problems, is developed.—P. F.

Specifying the Heat-Exchanging Efficiency of Cooling Towers and Gas Coolers. H. Rögener. (*BWK*, 1954, **6**, Nov., 440–443). The parameter sA/w, also known as the " tower performance factor," is theoretically and experimentally shown to be essentially independent of the actual thermal state of the heat-exchange system. Here s is the specific evaporation rate of the coolant per unit area, A the area over which heat-exchange occurs, and w the water throughput in unit time. The parameter is thus particularly suited for the specification and evaluation of the efficiency of ventilating and cooling systems.—P. F.

The Classification of Fine Middlings with a Belt Heavy-Medium Separator. J. R. Schönmüller. (*Techn. Mitt. Krupp*, 1954, **12**, (6), 144–156). A report is presented of trials with a new type of classifier for treating coal middlings down to 0·5 mm. with a gravity of about 2·0. The middlings are fed on to one end of a trough-shaped rubber belt immediately in front of the nozzle supplying the heavy medium. The endless belt trough is 500 mm. wide with sides 150 mm. high; the end rollers over which it passes are 1500 mm. in dia. and 20 m. apart. The heavy medium is fed so that it travels at the same rate as the belt, and if this moves at 1·2 m./sec. the fractionating time is 17–18 sec. Vanes at the end of the belt can be set to fractionate the flow at the desired level. The designed capacity is 20 to 40 tons of middlings per hr. Fine fractionating at very high efficiency was achieved.—R. A. R.

The Mechanical Drying of Coals and Very Fine Ores: Actual Limits and Improvements. J. Dodelet. (*Publ. Assoc. Ing. Faculté Polytechn. Mons.*, 1954, (3), 11–28). The difficulties involved in drying coal apply also to the drying of fine ores. Known theories are restated, and the general principles of drying and filtering are discussed. The influence of various factors on drying and filtering are experimentally investigated.

REFRACTORY MATERIALS

Central Research Department of Morgan Crucible Company. (*Engineering*, 1954, **178**, Dec. 3, 729–730 : *Brit. Steelmaker*, 1954, **20**, Dec., 468–470). This article describes the newly established Central Research Department of the Morgan Crucible Company Ltd. which has taken over the duties formerly carried out by separate research units.—M. D. J. B.

The British Ceramic Research Association. A. E. Dodd. (*Metallurgia*, 1954, **50**, Oct., 174–175). Work carried out by this association on alkali and carbon monoxide attack of blast-furnace refractory linings is briefly reported.—B. G. B.

The Coefficient of Linear Thermal Expansion of Tridymite. J. B. Austin. (*J. Amer. Chem. Soc.*, 1954, Dec., **76**, 6019–6020). Inversion temperatures of 117° and 163°C. for tridymite have been confirmed and a drop in the coefficient of expansion at two higher temperatures, 210° and 475°C., has been demonstrated.—J. O. L.

Petrographic Studies on Chrome-Magnesite and Magnesium Silicate Refractories. J. C. Banerjee. (*J. Sci. Indust. Res.*, 1954, **13**, Oct., 727–732). Refractories made from Indian raw materials have been studied and compared with European and American supplies. Petrographic study has shown that the refractoriness-under-load value decreases with the forsterite (2 $MgO.SiO_2$) content, which should be at least 40% for high values at 1700°C.—J. O. L.

BLAST-FURNACE PRACTICE AND PRODUCTION OF PIG IRON

The Chemical Basis of the Manufacture of Iron and Steel. D. J. O. Brandt. (*Chem. Indust.*, 1954, Aug. 7, 982–987). The main chemical reactions occurring in the blast-furnace during the reduction of iron ore to iron and in the various processes employed for the conversion of the latter product to steel are considered in detail, with particular reference to some modern developments.—J. O. L.

Ironmaking at the Ford Motor Company, Limited, Dagenham. (*Iron Coal Trades Rev.*, 1954, **169,** Oct. 15, 903–922). The equipment and techniques employed in ironmaking at Ford Motor Co. Ltd. are reviewed. Following an account of the handling of raw materials at the docks and stockyards, details are given of the blast-furnace, producing 500–600 tons/day of foundry iron, and of its ancillary equipment including the hot-blast stoves, pig-casting machine, and Dwight-Lloyd sinter plant fired by blast-furnace or coke-oven gas. The construction and layout of the Coppee coke-oven plant and of the coal and coke handling plant are then described, and finally details are given of the by-product plant.—G. F.

Survey of Blast-Furnace Investigations in Russia. (*Iron Coal Trades Rev.*, 1954, **169,** Nov. 26, 1265–1270). The information obtained in extensive blast-furnace research in Russia and the conclusions reached by the Russian workers are outlined. The factors investigated include descent of the burden in the stack, gas composition, temperature and pressure in stack and bosh, reduction of iron ore during burden descent, formation of primary slags, tuyere level studies, and re-oxidation of iron in the combustion zone.—G. F.

Blast-Furnace Exploration : Use of a Continuous Flow Counter. T. W. Johnson and D. Meachen. (*Research*, 1954, **7,** Sept., 356–359). The use of a proportional flow counter in measuring gas transit time through the burden is described. A method of introducing a succession of pulses in a short period, coupled with a high-speed recorder, enables a number of results to be obtained rapidly, the accuracy of each being 0·2 sec.—K. E. J.

Blast-Furnace Operation in the Yawata Iron and Steel Works Today. K. Wada. (*Tetsu to Hagane*, 1954, **40,** Aug., 755–761). [In Japanese]. Details are given of the performance of six furnaces, producing basic and foundry iron, ranging in capacity from 350 to 1,000 tons/day. In spite of coke of 13% ash content, performance has recently been improved ; the coke rate has fallen and the largest furnace has reached 1250 tons/day output. This is attributed to raw materials sizing, extended sintering capacity and improvements in coke properties.—K. E. J.

The Electric Smelting of Iron Ore. W. M. Armstrong. (*Trans. Canad. Min. Met.*, 1954, **57,** 517–522 : *Bull.*, 1954, **47,** Aug., 517–522). The development of the electric pig iron process is traced. The design and operation of some modern furnaces are described, those at present in use having connected electrical loads ranging from 4000 to 13,000 kVA. The latter unit produces 100 long tons pig-iron/24 hr. from magnetite sinter containing 58% Fe. Four units, each with 20,000 kVA. input, under construction in Norway, will produce a total of over 700 tons/day of pig iron. Reactions occurring in the furnace are discussed, including sulphur removal, and the use of complex ores containing titanium, chromium, or vanadium. Operating costs are compared with those for a blast-furnace, and are quoted for a particular case, as $34.45/2000 lb. of pig iron for electric smelting, and $31.55/2000 lb. for blast-furnace operation. Capital costs cannot be compared, chiefly because of differences of productive capacities. The metallurgical, and, in some cases, economic advantages of electric smelting are discussed.—T. E. D.

Rate of Desulphurization of Carbon-Saturated Iron by Blast-Furnace Slags. C. E. A. Shanahan. (*J. Iron Steel Inst.*, 1955, **180,** June, 140–144). [This issue].

PRODUCTION OF STEEL

The Design and Construction of Lackenby Steelworks. A. P. Clark and S. Cornforth. (*J. Iron Steel Inst.*, 1955, **180,** June, 180–188). [This issue].

Use of Models for Layout and Planning. J. C. Montoro. (*Iron Steel Eng.*, 1954, **31,** Sept., 154–158). The use of models for planning plant layout is discussed.—M. D. J. B.

Transport in Steelworks. J. Adamus. (*Hutnik* (Prague), 1954, **4,** (9), 258–260). [In Czech]. Transport in the Molotov Steelworks at Trinec was reorganized on the pattern now used in the Soviet Union. The new and abandoned methods are compared and the considerable increase in efficiency and the savings obtained with the latter are considered.—F. F.

Physical Chemistry and Steelmaking Practice : Is Physico-Chemical Research of Any Value to the Steelmaker ? D. J. O. Brandt. (*Iron Coal Trades Rev.*, 1954, **169,** Dec. 10, 1373–1377). The author critically examines the value to steelmaking practice of physico-chemical research, initially distinguishing between product-development and process-development research, and between development research and detached research. He concludes that physico-chemical research has lagged behind process development, and has not proved to be of practical value to the steelmaker.—G. F.

Developments at Consett Iron Works. (*Metallurgia*, 1954, **50,** Nov., 219–224). An account is presented of the development and recent reconstruction of the Consett Iron Works. Details are given of the extensions and developments in the works including the use of the duplex (Bessemer/open-hearth) process for steelmaking and the new ore handling plant at Tyne Dock.—B. G. B.

Conversion of Open-Hearth Furnaces to Oil-Firing. F. Bartu. (*Iron Coal Trades Rev.*, 1954, **169,** Dec. 31, 1557–1562). The author presents data and observations gained from a wide experience in the conversion of open-hearth furnaces from producer, coke-oven, or natural-gas firing to oil firing. The advantages and economics of oil-firing, the influence of the atomizing medium, the use of high-pressure jets, mixed oil and gas firing, and desirable alterations to the regenerator system are discussed.—G. F.

Observations of Stainless Steel Melting Practice. D. C. Hilty, H. P. Rassbach, and W. Crafts. (*J. Iron Steel Inst.*, 1955, **180,** June, 116–128). [This issue].

Bifurcated Spouts Increase Open Hearth Output. I—Close Supervision Prevents Tie-ups. C. N. Straney. **II—Increased Shop Tonnages Realized.** E. C. Sorrells. **III.—Double Heats Show no Decrease in Quality.** J. H. Kelly. **IV.—Brick Sleeve Solves Tapping Problem.** H. H. Northrup. (*Amer. Inst. Min. Met. Eng. Open Hearth Steel Conf.*, Apr. 5–7, 1954 : *J. Met.*, 1954, **6,** Oct., 1119–1123). The authors briefly outline their experiences with O.H. furnace bifurcated launders at Weirton Steel Co., Gary Works of United States Steel Co., Sparrows Point Works of Bethlehem Steel Co., and Buffalo Works of Republic Steel Co. respectively. In general the use of twin launders has permitted increased outputs, but extra care is required to prevent delays and to ensure equal division between the two ladles.—G. F.

Studies on the Decarbonization Reaction of Molten Fe-C Alloys (II). Y. Katsufugi and K. Niwa. (*Tetsu to Hagane*, 1954, **40,** Oct., 973–979). [In Japanese]. The effect of oxygen pressure on the decarburization of Fe-C alloys containing 1–4% carbon was studied by varying the partial pressure of oxygen in the atmosphere and the area of gas-liquid interface. It is concluded that reaction proceeds through oxygen molecules dissociating on adsorption at the interface, the atoms then diffusing into the surface layer to participate in the reaction. Increase in CO pressure retards the reaction.—K. E. J.

Large Electric Furnaces. D. F. Campbell. (*J. Iron Steel Inst.*, 1955, **180,** June, 107–113). [This issue].

The Operation of a 60-ton Arc Furnace. At Samuel Fox and Co., Ltd. R. Wilcock. (*J. Iron Steel Inst.*, 1955, **180,** June, 113–116). [This issue].

Europe's Largest Arc Furnace. (*Brit. Steelmaker*, 1954, **20,** Dec., 458–464 : *Electrical Times*, 1954, **126,** Dec. 16, 888–889 : *Engineer*, 1954, **198,** Dec. 17, 843–846 : *Iron Coal Trades Rev.*, 1954, **169,** Dec. 17, 1437–1442: *Engineering*, 1954, **178,** Dec., 24, 830–831 : *Refractories J.*, 1955, Jan., 26–32, 34, 35 : *Electrical J.*, 1954, **153,** Dec. 17, 1953–1954 : *Foundry Trade J.*, 1954, **97,** Dec. 23, 741–746 : *Metallurgia*, 1955, **51,** Jan., 3–8 : *Iron Steel*, 1955, **28,** Jan., 11–13). A new Birlec 60-ton electric arc furnace, the largest in Europe, has recently been inaugurated at the Stocksbridge works of Samuel Fox & Co. Ltd., and is expected to produce over 1000 ingot tons per week of low-alloy steels. Details are given of the furnace, which combines the latest features of both European and American design, and of the rest of the development plan embracing a complete electric melting shop and a new stockyard.—G. F.

Electric Steel Production : I.—Sulphur and Hydrogen Removal ; II.—Chromium in Electric Furnace Steel ; III.—The Use of Oxygen in the Electric Arc Furnace ; IV.—Technological Developments. D. D. Howat. (*Iron Steel*, 1954, **27**, June, 223–227 : July, 341–345 ; Aug., 403–407 ; Sept., 446–450). In Part I of this critical review the author first briefly considers the economics of electric steelmaking and then discusses the thermodynamic and practical aspects of sulphur in the electric furnace. Hydrogen is then dealt with, and the methods of sampling and analysis, the sources of hydrogen and methods of eliminating it, including inert-gas flushing, are discussed. Part II is concerned with chromium in electric furnace steel, and the thermodynamics of the chromium-oxygen equilibrium are first dealt with. The distribution of chromium between acid and basic slags and the liquid metal is then discussed, and the refining of high-chromium steels, including those very low in carbon, is considered. Part III deals with oxygen injection in electric furnace steelmaking, with particular reference to basic practice and to the manufacture of austenitic stainless steels. The main technological developments considered in Part IV are the introduction of top-charge furnaces, high rates of melting and increase transformer capacity, improved methods of electrode control, and electro-magnetic stirring. A cost comparison with open-hearth practice is also discussed. (166 references).—G. F.

The Söderberg Self-Baking Electrode. M. O. Sem. (*J. Electrochem. Soc.*, 1954, **101**, Oct., 487–492). Differences between the electrode paste for pre-baked and self-baking electrodes are discussed. The recent application of the electrode to steel-melting furnaces is described.—A. D. H.

Viscosity and the Structure of Molten Silicates. J. O'M. Bockris and D. C. Lowe. (*Proc. Roy. Soc.*, 1954, **226A**, Dec. 7, 423–435). A magnetically controlled null-point modification of the rotating crucible viscometer enables viscosity measurements to be made up to 1850°C. It has been applied to the $CaO–SiO_2$ system with results differing from those obtained in graphite crucibles. Flow, viscosity isotherms, and energy of activation results are given ; they are inconsistent with the Endell and Hellbrügge theory of liquid silicates and glasses, and indicate an ionic structure. (48 references).—K. E. J.

Preliminary Studies on the Properties of Calcium Carbide for Metallurgical Purposes. C. E. A. Shanahan and F. Cooke. (*J. Appl. Chem.*, 1954, **4**, Nov., 602–611). Production of a CaC_2-bearing slag, fluid at iron- and steel-making temperatures, may assist desulphurization. Techniques for determining the composition and melting points of such slags are described, and information on the solubility of the carbide in various slags, confirming thermodynamic calculations, is presented.

Slag–Metal–Graphite Reactions and the Activity of Silica in Lime–Alumina–Silica Slags. J. C. Fulton and J. Chipman. (*Trans. Amer. Inst. Min. Met. Eng.*, 1954, **200** : *J. Met.*, 1954, **6**, Oct., 1136–1146). In a further study of the reduction of silica from blast-furnace slags by carbon-saturated iron, the authors have established the silicon-silica relation in the range 1425–1700°C. for slags containing up to 20% Al_2O_3. The activities of SiO_2 and CaO in their binary solutions at 1600°C. have been determined, and the effect of 10–20% Al_2O_3 and 10% MgO additions on the activity of SiO_2 has been noted. Silicon carbide is formed by reaction of graphite with high-silica slags and the conditions for its formation are given.—G. F.

Continuous Casting Process now in Commercial Production. C. Longenecker. (*Blast Furn. Steel Plant.*, 1954, **42**, Nov., 1292–1294). A brief illustrated account is given of a machine at Atlas Steels Ltd., Welland, Canada which uses the Rossi-Junghans principle. The ingots are either forged or rolled into tool or special steels.—B. G. B.

Study on the Local Exfoliation of the Ingot Mould. II. T. Kitashima and T. Kawano. (*Tetsu to Hagane*, 1954, **40**, Aug., 766–773). [In Japanese]. An account is given of research into combating exfoliation caused by local heating and rapid graphite growth. Means adopted included reducing the stripping time, controlling the manganese content of the mould steel, improving the mould design, and better arrangement of the moulds at the teeming mill. The special mould design includes open pipes in the wall to facilitate cooling.

PRODUCTION OF FERRO-ALLOYS

Some Factors Influencing the Production of Manganese from Open-Hearth Slags. J. A. Gregory. (*Australian Inst. Metals : Australasian Eng.*, 1954, Apr. 7, 47–53). In a previous paper (*J. Iron Steel Inst.*, 1954, **177**, July, 366) a full-scale production trial of the two-stage process for recovery of manganese from basic open-hearth slags was described. The present paper deals with the difficulties encountered during full-scale operation and describes how some of these were overcome. Further lines of investigation are suggested. (14 references).—P. M. C.

How USBM Metallurgists are Solving the Manganese Shortage. C. Prasky. (*Eng. Min. J.*, 1954, **155**, Nov., 72–75). To overcome the American shortage of manganese, a process has been devised for treating low-grade (7% Mn, 27% Fe) Cuyana ores. It consists of calcination followed by roasting in a shaft furnace in an SO_2/air mixture to produce $MnSO_4$, which is later leached out, the iron and phosphorus remaining in the residue. The SO_2 is derived from low-grade pyrite and pyrrhotite deposits, which also produce usable iron oxide.—K. E. J.

Recovery of Manganese from Ores of Aroostook County, Maine. R. T. MacMillan and T. L. Turner. (*U.S. Bur. Mines, Rep. Invest.*, 5082, Oct., 1954).

Ferromanganese Furnace Fumes Cleaned Successfully. C. H. Good, jun. (*Iron Age*, 1954, **174**, July, 95–97). A description of the plant and process at Duquesne Works, U.S. Steel Corp., is described. Since July 1953, 135,000 cu. ft./min. of gas from two ferromanganese furnaces have been cleaned, in five special units, 105 tons/day of dust being removed. The gas from the furnaces is cooled and humidified in conditioning towers, the fine particles are collected in electrostatic precipitators, and the gas passed to the clean gas main. The dust is oxidized, wetted, briquetted and stored.—D. L. C. P.

FOUNDRY PRACTICE

The British Cast Iron Research Association. J. G. Pearce. (*Metallurgia*, 1954, **50**, Oct., 180–182). A brief account of some of the activities of this association is given. Work on the elimination of dust hazards in the foundry, shell moulding, effect of gases in cast iron, the causes of enamelling defects, and the properties of nodular cast iron are mentioned.—B. G. B.

The British Steel Castings Research Association. J. F. B. Jackson. (*Metallurgia*, 1954, **50**, Oct., 183–186, 191). A short review of some selected items of the work of this association is made. These include the adherence of sand to steel castings, the mechanism of the freezing of steel, intergranular fracture, air/carbon-arc gouging process, swing-frame grinder dust control, automatic sampling of atmospheric dust, and a new radiographic exposure calculator.—B. G. B.

Use of Instruments to Control Cupola Operations. R. B. Muirhead. (*Foundry and Metal Treating*, 1954, **1**, June, 7–9, 12–16). The necessity for better and more complete melting control is emphasized. The author discusses the control and analysis of steel scrap and coke ; the importance of a correct volume of air and control of the blast ; gas analysis ; the use of a cupola pyrometer to control melting procedure ; and tests for fluidity and chill. Reference is also made to automatic methods for adding inoculants and alloys ; slag control ; and liquid metal height and charge height indicators.—P. M. C.

Suggestions for Improving Cupola Operations. (*Foundry and Metal Treating*, 1954, **1**, Apr., 23, 24). A brief review is given of the desirable features and operating conditions for successful production of metal from cupolas. Raw materials, linings, blast control, furnace and tuyere design, and charging techniques are dealt with.—P. M. C.

Spheroidal Graphite Cast Iron and Its Manufacture under Australian Conditions. F. T. Smith. (*Foundry and Metal Treating*, 1954, **1**, May, 23–32 ; June, 23–25, 32). The author reviews spheroidal graphite cast iron and its technology up to recent times. The history of its development and its fundamental metallurgy is described, with particular reference to the problem of unwanted elements and their unavoidable presence in Australian pig irons. (34 references).

Marine High Duty Cast Iron Replaces Steel. E. C. Pigott. (*Iron Steel*, 1954, **27**, Sept., 441–445). The Central Marine Engine Works, West Hartlepool, has had more than 100 heats of iron castings to B.S. 1452 Grade 20 specification accepted by Lloyd's in place of steel for saturated steam lines, 96% of the output meeting official acceptance after rigorous hydraulic and mechanical testing. The author gives the sequence of events leading to the choice of this material, and details the foundry procedure adopted.—G. F.

Investigation on Cast Iron Having Fine Graphites Produced by Melting Cast Iron Covered with Slag Containing TiO_2 (IV).

H. Sawamura and M. Tsuda. (*Tetsu to Hagane*, 1954, **40**, Oct., 986–990). [In Japanese]. Experiments adopting various time intervals showed that the eutectic structure was preserved even in iron kept molten for 60 min. after the slag was removed. For the new process the aluminium content should be kept as low as possible, and the CaO/SiO_2 ratio should be controlled.—K. E. J.

Production of Spheroidal Graphite in Cast Iron by Passing Argon through the Melt. P. König and B. Marincek. (*Schweiz. Arch. Wiss. Techn.*, 1954, **20**, Feb., 41–44). [In German]. When zinc is added to prevent sulphide segregations in high-sulphur irons containing less than 2·6%C and 0·1% Mn there is a tendency to form graphite spheroids. This is attributed to the removal of dissolved gases by the scavenging action of zinc vapour. A similar scavenging action produced by passing an inert gas, argon, through the melt had the same effect provided the manganese content did not exceed a value between 0·1% and 0·2%. With manganese at the higher limit, rapid cooling was necessary to produce spheroidal graphite, and greater concentration of manganese increased the oxygen solubility by forming a stable oxide.—H. R. M.

Practical Molding Sand Control. F. S. Brewster. (*Foundry*, 1954, **82**, Nov., 102–107). The various properties of a moulding sand are enumerated and grouped in order of their importance in a sand control programme. The importance of moisture, permeability, green strength and plasticity, dry strength, hot strength, and retained strength are then discussed. The frequency of testing and the design of a laboratory for routine sand control testing is briefly considered.

Fundamentals of Synthetic Molding Sand. N. J. Dunbeck. (*Foundry*, 1954, **82**, Nov., 108–111). The development of synthetic sand practice is summarized and the differences between naturally bonded and synthetic sands are outlined. The properties of the base sand and of clays are discussed together with the principles to be followed in choosing a synthetic sand with the required combination of properties.

Steel Foundry Molding Sand. J. B. Caine. (*Foundry*, 1954, **82**, Nov., 122–125). The composition and property ranges of the standard moulding sands used in steel foundries are given together with the modifications necessary for different sized castings. In particular, the methods of overcoming straining and metal penetration in large castings are discussed. The different types of base sands are considered and the effects of Western Bentonite, and cereal additions on casting quality are explained.—B. C. W.

Molding Sand Practice in the Malleable Foundry. L. E. Emery. (*Foundry*, 1954, **82**, Nov., 126–129). The types and requirements of base sands suitable for use in malleable iron foundries are considered with particular reference to the use of the same sand for both cores and moulds. The effects of additions of seacoal, bentonite, and fireclay on sand properties and casting quality are briefly discussed.—B. C. W.

Tempers Sand Automatically in a Continuous Mixer. R. H. Herrmann. (*Foundry*, 1954, **12**, Nov., 169–170). The system used at the Studebaker-Packard Corp., Detroit, for the automatic control of the moisture content of moulding sand is described. The moisture content, temperature, and volume of the return sand is continuously measured and results are automatically co-ordinated to control the water addition; bonding materials are also added continuously and automatically. Close control of moisture content reduces the number of scrap moulds and castings.—B. C. W.

Bimetallic Castings Achieved by Bonding Process. V. Delport. (*Foundry*, 1954, **82**, Sept., 102–105, 212, 214–215). A description is given of the production of aluminium pistons with cast iron groove linings bonded as an integral part of the casting. The inserts are cut from centrifugally cast cylinders, dipped in a molten aluminium alloy and then, while the bonding layer is still molten, they are transferred to a gravity die-casting machine where the aluminium piston is cast round them. The ring grooves are finally machined in the inserts.—B. C. W.

Proteus Turbine Casting Produced by Centrifugal Casting. (*Machinery*, 1954, **85**, Sept. 24, 647–652). The production of the turbine casing for the Bristol Proteus propeller-gas turbine unit is discussed. The mould parts, equipment used for spinning the moulds during pouring, and methods of cutting feeder heads from the casting are described.—M. A. K.

Close Tolerance Castings. M. W. Riley. (*Mat. Methods*, 1954, **40**, Sept., 121–136). The theme of this comprehensive review is that casting metals to close dimensional tolerances can substantially reduce the total cost of a product. The advantages and limitations of each of the following six basic types of close tolerance casting are discussed: plaster mould, permanent mould, shell mould, special sand, die, and investment. Materials, methods, design factors, and typical case histories are presented in each instance.—P. M. C.

10-Ton Capacity Holding Furnace. (*Engineer*, 1954, **198**, Sept. 17, 398). A brief description is given of a plant for remelting cast-iron swarf at the foundry of Hepworth and Grandage Ltd., Bradford. The plant comprises two 2-ton Efco induction furnaces and a 10-ton furnace held at 1450° C. Both induction and holding furnaces are tilting and operate day and night, casting taking place mainly in the daytime.

Cast Crankshafts for the Motor Industry. W. Kilian. (*Met. u. Giesserei Techn.*, 1954, **4**, Sept., 401–406). A method of casting crankshafts developed by the Zentralinstitut für Giessereitechnik, Leipzig, is described. Special malleable iron, nodular graphite iron, and a grey iron alloy are used. Cast crankshaft design and test data are discussed.—L. J. L.

The Application of Rare Earth Metals in Metallurgy. M. Ballay. (*Mem. Soc. Ing. Civils France*, 1954, Jan.-Mar., 80–88). The influence of cerium on the form of graphite in irons is first considered and examples of the use of cerium additions to irons in order to stabilize certain structures and the influence of the additions on the mechanical properties are given. The use of cerium additions to minimize the effect of impurities in iron which is to be treated with magnesium to form nodular graphite is explained. The influence of cerium on the mechanical properties of mild and stainless steels is discussed.—B. G. B.

Spheroidal Graphite Irons. A. Ross. (*Chimie Ind.*, 1954, **72**, Oct., 673–678). The processes occurring during the solidification of ordinary and spheroidal irons are considered. The atomic properties of graphite and the ionic properties of electropositive metals enable the author to propose a theory explaining the formation of graphite nodules by the action of ionic magnesium. This favours the formation of the allotropic α-modification of graphite.—B. G. B.

New Methods for the Wet Preparation of Fine Sand. H. Trawinski. (*Giesserei*, 1954, **41**, Aug. 19, 433–437). The various methods of wet beneficiation of fine sand such as sieving, sedimentation, and cyclone treatment are considered and the range of particle size for which each is most suitable is stated. Commercially available separating plants are described and illustrated. These include vertical and horizontal separators and pan separators designed by Dorr, Kamig, and Dorr-Eindicker.—R. J. W.

Foamed Gypsum as a Mould Material for Precision Casting—Basis of Foamed Gypsum Manufacture and Treatment. E. Piwowarsky and A. Schorr. (*Giesserei Technisch-Wissenschaftliche Beihefte*, 1954, July, (13), 685–700). The properties of gypsum in its various forms and its application as a moulding material are given. The porous nature of certain forms of gypsum makes it a useful moulding material. The preparation of foamed gypsum moulds and the necessary apparatus are described.—R. J. W.

The Value of Mould Hardness Measurements for Judging the Sand Consolidation Obtained with Moulding Machines. E. Piwowarsky and W. Patterson. (*Giesserei Technisch-Wissenschaftliche Beihefte*, 1954, July, (13), 673–683). The method of hardness testing is first described and the relation between hardness and other physical properties of the sand is shown. Hardness testers for moulding materials, and the effect of their characteristics on the results, are described. The influence of various factors on the reproducibility of the results is discussed. The influence of thixotropy on the hardness value is also dealt with.—R. J. W.

Accuracy, Shrinkage, and Machining and Casting Allowances when Making Patterns for Grey Iron and Steel Castings. F. Lamm. (*Giesserei*, 1954, **41**, Sept. 2, 465–468). The use, treatment, and behaviour of nine different moulding materials are tabulated. The form in which the materials are used and the treatment necessary to obtain the best results are given. The machining allowance and shrinkages for different dimensions of castings are illustrated graphically.—R. J. W.

The Use of Insulated Risers for Steel Castings. V. Batěk, A. Straka, and J. Kracík. (*Slévárenství*, 1954, **2**, (9), 267–270). [In Czech]. The preparation and use of insulating material made from fly ash is described. Carburization of the risers is prevented and metal losses are reduced with this insulation. Prefabrication of liners in the form of dried sleeves, or lining

in situ with subsequent drying are two possible methods of applying the insulation.—P. F.

Moulding Units for Steelworks Ingot Moulds. V. Brož. (*Slévárenství*, 1954, **2**, (7), 200–204). [In Czech]. The design and manufacture of a steel-framed moulding unit, claimed to be cheaper and simpler than those mentioned in the literature, are described. The four walls consist of either four separately cast ribbed plates or two separately cast L-section portions, which are clamped together and rest on a heavy rectangular base. Much less sand was used for casting these than is required for conventional ingot moulds.—R. A. R.

Moulding Units for 100 to 200 Ton Ingot Moulds. V. Brož. (*Slévárenství*, 1954, **2**, (8), 226–230). [In Czech]. Details of design, mode of production, and materials employed for moulds for ingots of 130, 150, and 170 tons are given, and the data are compared with corresponding ones for similar ingot moulds of standard designs. A new type of suspension is described.

The Production of Castings from Austenitic Manganese Steel. K. Weber. (*Slévárenství*, 1954, **2**, (10), 301–305). [In Czech]. The structure, physical properties, casting properties, casting temperatures, tendency to form shrinkage cavities, and wear resistance of several Hadfield steels made in Czechoslovakia are discussed.—P. F.

Structure of Rolling-Mill Rolls. C. Joseph. (*Echo Mines*, 1954, Oct., 671–674). Methods and materials used for making rolling-mill rolls are discussed. Examples are cited of forged and cast steel rolls and of cast and spheroidal graphite iron rolls. Details are given of the composition of the steels and irons, and also of the heat-treatment.—B. G. B.

Cast Difficult Parts in Mercury Pattern Moulds. D. Von Ludwig. (*Iron Age*, 1954, **173**, June 17, 148–150). The "Mercast" Process, in which frozen mercury patterns are used to make ceramic shell moulds for precision castings, is described. The method is notable for its ability to cast parts with unusual mass, thin section, complex contours, extreme accuracy, and high surface smoothness.—D. L. C. P.

The Sand Spun Pipe Plant and Foundry of the Stavely Iron and Chemical Co. Ltd. (*Refract. J.*, 1954, **30**, Aug., 350–353). The article records a visit to the above plant. The production procedure is explained. Sand spun pipes are 8 to 24 in. in dia. and 16 ft. long. Metal spun pipes range from 2½ to 7 in. dia. and up to 18 ft. long.—D. L. C. P.

Ingot Mould Foundry: Baglan Engineering Complete New Works at Neath. (*Brit. Steelmaker*, 1954, **20**, Sept., 362–363). The new Melyn foundry and engineering plant of the Baglan Engineering Co. (1919) Ltd. has recently been completed. A brief description of the works is given.—G. F.

The Production of Turbine Blades by the Investment Casting Process. (*Machinery*, 1954, **85**, Oct. 1, 699–708; Oct. 8, 751–761). **Napier's Investment Foundry.** (*Aeroplane*, 1954, **87**, Nov. 19, 730–731). **Investment Castings.** (*Automobile Eng.*, 1954, **44**, Sept., 367–373). Methods employed in the investment foundry of D. Napier and Son Ltd., London, are described. The use of aluminium alloy patterns with accurate shrinkage allowance from which soft-metal wax dies are prepared, and optical equipment specially designed for checking accuracy are discussed together with the casting of dies and surface finish obtained.

Investment Precision Casting without Expendable Patterns. A. Dunlop. (Inst. British Foundrymen: *Amer. Foundryman*, 1954, **25**, June, 64–69). A new precision investment casting process using permanent patterns and refractory moulds is described. The moulding material is a slurry of a suitable refractory filler with a colloidal suspension of silica in alcohol and a gelling reagent. The hydrolysis of the ethyl silicate causes the slurry to solidify as a tough rubbery gel from which the moulds may be readily withdrawn. The rubbery mould pieces are then rapidly fired by igniting the alcohol which has formed during the hydrolysis. The rapid firing produces a mould full of fine cracks so that no overall contraction takes place and the mould cavities have the same dimensions as the pattern. The cracks render the moulds permeable to gases but are too fine to allow metal penetration. The process is suitable for any castable metal or alloy, and steel castings weighing up to 300 lb. have been successfully prepared.—B. C. W.

The Calculation of the Coefficient of Resistance to Flow of Molten Metals. E. S. Rabinowitsch. (*Doklady Akademii Nauk, U.S.S.R.*, 1946, 395: *Met. u. Giessereitechn.*, 1954, **4**, Sept., 411). W. Ruff's formula for calculating the coefficient of resistance to flow is quoted; an alternative formula, based on Bernoulli's equation, is derived: the results of calculations by the two formulæ are compared and Ruff's is rejected, his results being too low.—L. J. L.

Revised Spiral Test Relates Fluidity to Phase Diagram. W. A. Spindler, W. B. Pierce, and R. A. Flinn. (*Amer. Foundryman*, 1954, **26**, Sept., 56–58). A simplified green sand fluidity spiral is described and it is shown that the reproducibility is about 2 in. of spiral length. With shell moulded spirals an increase of 2–4 in. was obtained for the same pouring temperature. Data obtained for seven different metals show that the fluidity is a linear function of the superheat above the liquidus.—B. C. W.

Casting Defects and Their Causes. Part V. (*Gjuteriet*, 1954, **44**, Sept., 149–156). [In Swedish]. In its fifth report a Swedish committee analyses the defects caused by sections of the mould walls being loosened or washed away before solidification occurs.—G. G. K.

Development of the Lost-Wax Process of Precision Casting, 1949–53. J. S. Turnbull. (*Inst. Mech. Eng., Advance Copy*, Dec. 31, 1954). The limitations of the original lost-wax process (1945–49) are outlined and a description is given of improved methods developed in the Precision Casting Shop of the Metropolitan-Vickers Electrical Co. Ltd. These developments include wax injection techniques, the elimination of "draw" in wax patterns, increasing pattern size and accuracy, and the new Investment X-technique, full details of which are given.—P. M. C.

Mechanization of Shell Moulding. A. Dunlop. (*Metal Ind.*, 1954, **85**, Aug. 27, 163–167; Sept 3, 192, 193). The principles and basic operations involved in the production of shell moulds are described, and recent developments in the design of automatic machines for the economic production of shell moulds are discussed.—P. M. C.

Shell Moulds and Cores. Important Developments in Polygram Equipment. (*Automobile Eng.*, 1954, **44**, July, 281–284). Details and illustrations are given of the latest mould makers and core makers in the Polygram range of equipment.—P. M. C.

International Harvester Finds Gray Iron Shell Mold Castings. K. Rose. (*Mat. Methods*, 1954, **40**, Aug., 102–104). Experience gained by the International Harvester Co., (U.S.A.), in the uses and production of small engine parts made by the shell moulding process is briefly discussed. Several advantages are claimed, such as improved strength in thin sections, better surface and dimensional accuracy, and lower overall production costs.—P. M. C.

British Melting Furnaces for Tata Foundries. (*Brit. Eng.*, 1955, **37**, Jan., 244–245). Details are given of two 4-ton and two 7-ton Birlec-Lectromelt electric arc furnaces being constructed for the Tata Locomotive and Engineering Co. Ltd., India; the continuous outputs will be 2 and 1¼-1½ tons/hr. respectively. The furnaces are top-charged, and amplidyne control is used on the electrodes.—K. E. J.

Automobile Castings. Advanced Techniques Employed by West Yorkshire Foundries Ltd. (*Automobile Eng.*, 1954, **44**, Oct., 409–416). A general description is given of the plant, products, and equipment at West Yorkshire Foundries Ltd., Leeds. The weekly production by 1100 employees is 300 tons of iron castings and 42 tons of aluminium. Details are presented of cylinder block and flywheel housing production, and of gravity die-casting techniques.—P. M. C.

How Quality Control Can Affect Casting Costs. R. N. Laveen. (*Product Eng.*, 1954, **25**, Aug., 169–171). It is pointed out that the cost of quality control is often forgotten when assessing the cost of production. Items such as additional drawings, radiographic inspection, production and testing of sample test bars, pressure testing and sealing of leaks are often forgotten. As an example, quality control increased the cost of casting a simple housing by 50%; it became cheaper to machine it from the solid.—A. M. F.

Stress *v.* Strain in Hot Tearing. J. B. Caine. (*Foundry*, 1954, **82**, Aug., 76–79, 233–238). Recent work on hot-tearing in castings is reviewed and the interpretation of the results in terms of the stress and strain theories of hot-tearing is discussed. The author considers that the strain theory is much more satisfactory in explaining the results and that the work of Middleton shows that the sand is a more important variable than the pouring temperature.—B. C. W.

Casting Defects, Their Cause and Methods of Prevention. N. L. Bush. (*Australian Inst. Metals: Australian Eng.*, 1954, Apr. 7, 63–71). Information is presented concerning

casting defects which are within the control of the metallurgist, i.e. those associated with the metal and the moulding sand. Attention is given to sand defects originating from such very different sources as hot sand and clay balls. Attention is drawn to practices leading to the presence of dissolved hydrogen. Inverse chill in cast iron is also discussed.—P. M. C.

Profitable Use of Exhaust Fume. R. J. Ruff. (*Amer. Gas Assoc. : Indust. Heating*, 1954, **21,** Aug., 1583–1592, 1660–1664). The author reviews the factors influencing profitable recovery from ordinarily non-inflammable waste gases containing organic by-products, e.g. from coke-ovens, by the use of catalysts. The process also reduces air pollution.—A. D. H.

Dust Suppression in Foundries. W. B. Laurie. (*Indust. Heating Eng.*, 1954, **16,** Sept., 263–265). Foundry dust most hazardous to health lies in the size range 0·8 to 1·0μ, but the amount of this size present is often only 1% of the total dust, so the determination of size range is important. After briefly discussing dust observation, general ventilation and local exhaust ventilation are considered. Specific examples of dust control on fettling benches and a 14-in. stand grinder are given.—T. E. D.

X-Ray Analysis of Foundry Dusts.—Fluorescent Spectral Analysis for Iron. G. L. Clark and H. C. Terford. (*Analy. Chem.*, 1954, **26,** Sept., 1416–1418). The X-ray fluorescent spectral analysis, using a recording Geiger counter unit, is described for the determination of iron in foundry dusts. Working calibration curves and results of analyses are given. The method is more reliable and convenient than chemical analysis.—T. E. D.

Smog Control in the Foundry. H. Dok. (*Amer. Foundryman.*, 1954, **26,** Dec., 46–49).

X-Ray Analysis of Foundry Dusts for Quartz and Iron in Relation to Silicosis and Siderosis. G. L. Clark, W. F. Loranger and S. J. Bodnar. (*Analy. Chem.*, 1954, **26,** Sept., 1413–1416). The X-ray diffraction method of Clark and Reynolds is improved and adapted for use with two different recording Geiger-counter diffractometers with a linear proportionality between α-quartz concentration and corrected intensity ratios in each case. Results on foundry dust samples are quoted.—T. E. D.

Safety Works—If you Work at it! H. A. Forsberg. (*Foundry*, 1954, **82,** Aug., 80–83, 192–194). A description is given of the safety programme carried out in the steel foundries of the Continental Foundry and Machine Co., East Chicago, Ind. The programme has brought about a considerable reduction in the accident frequency rate at their three foundries.—B. G. W.

HEATING FURNACES AND SOAKING PITS

A Work Horse for Industry—The Walking Beam Furnace. W. A. Darrah. (*Metal Treating*, 1954, **5,** July-Aug., 10, 11). The design and uses of walking beam furnaces are described. In the hearth are one set of bearer bars (beams) which continually rise and fall, and another set which move horizontally backwards and forwards. There is thus no endless belt carrying heat out of the furnace.—P. M. C.

HEAT-TREATMENT AND HEAT-TREATMENT FURNACES

Steel Supplier Has Modern Plant for Customer Service. A. Q. Smith. (*Metal Treating*, 1954, **5,** July-Aug., 12, 13). Details are given of an annealing installation at the Korhumel Steel and Aluminium Co., Illinois. Inert gas, bell type furnaces deal with about 5000 tons of strip per month.

Heat-Treatment of High-Speed Steel. S. G. Cope. (*Metal Treatment and Drop Forg.*, 1954, **21,** Jan., 3–10 ; Feb., 67–74, 81 ; Mar., 123–130, 137 ; Apr., 183–190, 204 ; May, 225–233 ; June, 295–302 ; July, 343–347 ; Aug., 365–368). The author surveys the published work on research and development in the heat-treatment of high-speed steel. (136 references).

Mechanization and Application of Salt Bath Furnaces. L. B. Rosseau. (*Metal Treating*, 1954, **5,** July-Aug., 2, 3, 26–32). A review is presented of available American Salt bath equipment, followed by details of its applications in neutral hardening, high-speed steel tool hardening, cyaniding, carburizing, interrupted quench treatments, annealing, solution heat-treatment, descaling, brazing, and heating for forging.—P. M. C.

Controlled Atmospheres for Heat Treatment of Metals : Methods and Equipment. E. S. Lanning, jun. (*Steel Processing*, 1954, **40,** July, 447–454, 458). The effects of various atmospheres on the oxidation and decarburization of both non-ferrous and ferrous metals at heat-treating temperatures are discussed. The choice of suitable atmospheres is dealt with, and generating equipment for ammonia, and mixtures of carbon monoxide and dioxide, nitrogen, and hydrocarbons is described and schematically illustrated.—P. M. C.

Heat Treatment Plant. Birlec Gas Carburizing Equipment Employed by Fodens, Ltd. (*Automobile Eng.*, 1954, **44,** Oct., 429, 430). Brief details are given of two Birlec pit-type gas carburizing furnaces which are arranged for drip-feed operation and are rated at 65 kW. The furnaces are giving an output of 12 to 14 tons/week of carburized parts (primarily gearbox components).—P. M. C.

Drip Feed Gas Carburizing. (*Metallurgia*, 1954, **50,** Nov., 239–241 : *Brit. Engineering.*, 1954, **37,** Dec., 214–215 : *Sheet Metal Ind.*, 1954, **31,** Dec., 1024–1026 : *Aircraft Prod.*, 1954, **16,** Nov., 466–468 : *Automobile Eng.*, 1954, **44,** Dec., 549–552). **Gas Cementation.** (*Iron and Steel*, 1954, **27,** Nov., 519–521). The development by Wild-Barfield Electric Furnaces Ltd., of a process which uses an organic liquid dripped directly into the carburizing furnace chamber to produce the reaction gas, is described. This "carbodrip" process has certain advantages over orthodox gas carburizing, particularly with regard to costs.—B. G. B.

Criticism and Comparison of Heat-Treating Facilities in Cold Rolling Mills. E. Schauff. (*Iron Coal Trades Rev.*, 1954, **169,** Dec. 10, 1385–1393). The author critically compares the heat-treating facilities and equipment in cold-rolling mills, dealing with pot annealing furnaces, roller-hearth furnaces, cover annealing furnaces, and continuous strip annealing furnaces. Two important factors, namely the metallurgical properties to be attained in the annealed material and the economy of the process, are considered in detail.—G. F.

Theory of Gas Atmospheres. A. G. Hotchkiss. (*Metal Progress*, 1954, **66,** Nov., 81–84). **Theory of Gas Furnace Atmospheres.** A. G. Hotchkiss. (*Indust. Heating*, 1954, **21,** Nov., 2212–2222, 2348). The effects of various gas atmospheres on hot ferrous and non-ferrous metals are shown and four diagrams of equilibria for gas-steel reactions are presented, some of the curves being applied to predict the composition of atmospheres suitable for carburizing in certain cases.

R. A. R.

Exothermic Atmospheres—Their Generation and Application. W. H. Boyd. (*Metal Progress*, 1954, **66,** Nov., 86–89). A short account of the exothermic type of gas generator for protective atmospheres is given. When dried to dew points of about —40°F. the gas mixture is very suitable for continuous furnaces which require entrances and exits to be open at all times.—B. G. B.

Endothermic Atmosphere, R. J. Perrine. (*Metal Progress*, 1954, **66,** Nov., 89–93). The temperature variation within the catalytic mass and other factors affecting the composition of the prepared gas and its stability after entering the heat-treatment furnace, are discussed.—B. G. B.

Dry Nitrogen as a Base for Prepared Atmospheres. D. Beggs. (*Metal Progress*, 1954, **66,** Nov., 94–98). Very dry atmospheres containing nitrogen and hydrogen have proved useful in heat-treatment furnaces and for purging explosive mixtures. Methods of manufacture are outlined and commercial equipment is illustrated.—B. G. B.

Dissociated Ammonia. M. R. Ogle. (*Metal Progress*, 1954, **66,** Nov., 99–101). The use of dry cracked ammonia for the bright heat-treatment of stainless and high-nickel alloys, for reducing oxides or decarburizing is described.—B. G. B.

Atmosphere Analysis and Control. W. L. Besselman. (*Metal Progress*, 1954, **66,** Nov., 102–105). New automatic equipment for the continuous analysis of gas mixtures encountered in heat-treating furnaces is discussed. The gases include CO_2, CO, CH_4, NH_3, oxygen, and hydrogen.

Elements of Gas Carburizing. W. Holcroft. (*Metal Progress*, 1954, **66,** Nov., 106–109). **Fundamentals of Gas Carburizing.** W. Holcroft. (*Indust. Heating*, 1954, **21,** Nov., 2196–2202, 2364). Reasons for employing gas carburizing and the requirements of an efficient plant are given briefly. An example is worked to show how to calculate the atmosphere composition for case carburizing a 0·60% carbon steel at different temperatures. Data are also presented for calculating the time required to produce a given case depth under certain conditions.—R. A. R.

Equilibrium Relationships for Dew Point Control. N. K.

Koebel. (*Metal Progress*, 1954, **66**, Nov., 110–114). The equilibrium between H_2, H_2O, CO and CO_2 and iron, iron oxides, and carbides is described and the author discusses how, for the endothermic type of gas atmosphere, adequate control of the composition can be obtained by maintaining the dew point in the furnace at the correct value.—B. G. B.

Dew Point Control in Practice. O. E. Cullen. (*Metal Progress*, 1954, **66**, Nov., 114–118). The determination of moisture in furnace gases is much quicker and more accurate than measuring the CO_2 content, so that the modern trend for the control of furnace atmosphere where accurate control of the surface or depth of carburizing is required is to measure the dew point.—B. G. B.

Carbo-Nitriding. H. N. Ipsen. (*Metal Progress*, 1954, **66**, Nov., 119–120). A brief account of the gaseous carbo-nitriding process is given.—B. G. B.

Neutral Heat Treatment. A. W. Frank. (*Metal Progress*, 1954, **66**, Nov., 121–122). A brief description of the use of gas mixtures containing no oxygen-bearing gases for heat-treatment is given.—B. G. B.

Induction Heat Treating. H. B. Osborn, jun. (*Metal Progress*, 1954, **66**, Nov., 125–129). Examples are given of automatic induction heating equipment for hardening steel specimens of various sizes.—B. G. B.

Large Car Type Furnace for Stress Relieving Weldments Installed by Westinghouse. (*Indust. Heating*, 1954, **21**, Aug., 1526–1530, 1674). A car bottom furnace designed to take a charge 30 ft. by 18 ft. by 16 ft. weighing up to 100 tons is described. The operating range is 1175–1600°F.—A. D. H.

Annealing Steel and Brass Shell Cases. W. M. Hepburn. (*Indust. Heating*, 1954, **21**, Aug., 1496–1508, 1672–1674). The plant is described. Roller hearth convection furnaces are used at 750–1250°F. The charge is carried in baskets.

FORGING, STAMPING, DRAWING, AND PRESSING

One of Our Country's Largest Forging Plants. H. E. Trent, jun. (*Steel Processing*, 1954, **40**, July, 422–436, 467). A very full description is presented of the modern Canton (U.S.A.) Forge Plant of the Ford Motor Company. This works occupies approximately 14 acres. Production, production engineering, quality control, metallurgical control, industrial relations, and utilities and services are dealt with.—P. M. C.

Nut and Bolt Production by Forging Methods. R. R. Clark. (*Australian Machinery and Production Eng.*, 1954, **7**, Apr., 4–6, 8–10). Both hot and cold methods for the production of nuts and bolts are described. Automatic machines are described and illustrated, and the intermediate operations and stages in each process are dealt with.—P. M. C.

Waste Steam Recovery at a Steelworks. (*Indust. Heating Eng.*, 1954, **16**, Oct., 296–299). At the Sheffield Works of Thos. Firth and John Brown Ltd., the process steam after use in steam hammers, is fed into a space heating system. There is no clogging of the condensing system by oil from the steam hammers because colloidal graphite is used for lubrication. The graphite injection system and space heating system are briefly described.—T. E. D.

The Design of Simple Dies for Bending Operations. W. M. Halliday. (*Sheet Metal Ind.*, 1954, **31**, Sept., 729–732). The design, action, and operation of two dies developed specially for the press forming of a small circular clip (or cleat) are described in detail.—P. M. C.

Flow-Form Dimpling Operations. G. C. Close. (*Machinery*, 1954, **85**, Sept. 3, 499–500). Countersunk holes for flush-head rivets and screws are now hot-coined in many types of metal sheet at the works of the Northrop Aircraft Corp., Hawthorn, Calif., U.S.A. Termed "flow-form dimpling," the method is based on the use of dies which are heated by an electrical resistance.—M. A. K.

Choose from Four Methods to Bulge Shells. S. R. Cope. (*Machinist*, 1954, **98**, Oct. 22, 1888–1891). Four different methods are employed to expand or bulge drawn shells. These are : (1) Direct action ; (2) expanding segments (mechanical) ; (3) rubber punch ; and (4) fluid (oil or water). The designs for three kinds of dies are given. In addition, rules for calculating the shell are provided.—M. A. K.

Presswork in the American Aircraft Industry. (*Welding and Metal Fab.*, 1954, **22**, July, 261–264). Hydraulic forming now widely used in the American Aircraft industry refers to methods whereby hydraulic fluids are directly used to exert forming forces on metallic stock materials. A description is given of the Wheelon process developed by Douglas Aircraft Company and the Formall process developed by Engle Aircraft Specialities.—U. E.

Determination of the Drawing Properties of Sheet—Use of the "Flex Tester." (*Sheet Metal Ind.*, 1954, **31**, Sept., 746, 747). Two simple dial-gauge type instruments have been developed by Jones and Laughlin Steel Corp. to predict the drawing of steel sheets. The Flex Tester measures the resistance of the material when its corner is bent through 60°, and a second instrument, the Spherometer, measures the curvature (permanent set) when the Flex Tester is removed. The Flex Tester indicates, in arbitrary units, the ease with which the sheet will draw, whilst the Spherometer indicates its tendency to form stretcher strain markings. Consistent and valuable information is obtained.—P. M. C.

Die for the Piercing of Accurately Aligned Holes. W. M. Halliday. (*Sheet Metal Ind.*, 1954, **31**, Oct., 842–844, 846). Details of the construction and operating features of a specially designed piercing die are given. The die produces **U**-shaped components having two accurately aligned holes of different diameters in the side arms.—P. M. C.

The Elastic-Plastic Theory of Containers and Liners for Extrusion Presses. M. R. Horne. (*Indust. Mech. Eng.*, 1954, *Reprint*, Nov. 1). Reasons are given for basing the design of containers and liners on elastic-plastic behaviour. After a review of the behaviour of thick tubes and rings beyond the yield point (according to available theories) a solution based on the stress-difference theory of elastic breakdown is adopted. The application of this theory to containers both with and without liners is elaborated and expressions are derived for the internal pressures sufficient to cause initial yield and full plasticity. Consideration is given to the possible occurrence of alternating yield on the inner surface of either the liner or the container. (14 references).—P. M. C.

The Mechanism of a Simple Deep-Drawing Operation. H. W. Swift. (*Sheet Metal Ind.*, 1954, **31**, Oct., 817–828). The author reviews investigations at Sheffield University on the drawing of a cylindrical shell from a flat circular blank. Representative experimental results are reported on blank-holding, radial drawing, and stretch-forming, and comparisons are made with theory where this has been developed to a useful stage. In general, drawing over the die is fairly well understood, but stretch forming over the punch needs much further investigation. A cup-drawing test for drawability, based on a punch having a hemispherical head is considered a good one.—P. M. C.

Rolled Extrusion of Thin-Walled Parts. (*Machinery*, 1954, **85**, Sept. 3, 484–487). The "Uniskan" extrusion process simplifies the production of fragile, cylindrical parts with wall thicknesses $< 0{\cdot}001$ in. The article describes the manufacture of a heat isolating support of Kovar, an alloy containing 53% Fe, 29% Ni, and 17% Co.—M.A.K.

Stretching Hot-Rolled Bars to Obtain "Cold-Drawn" Properties. J. A. Helget. (*Machinery*, 1954, **85**, Oct. 29, 925–927). The Hufford Machine Works Inc., El Segundo, California, have recently developed a machine which produces the mechanical properties of cold-drawn steel by merely stretching hot-rolled stock. In addition, the operation provides bars of the desired size, accurate throughout their entire length within a few thousandths of an inch. Scale resulting from hot-rolling is loosened and can be removed without pickling.—M. A. K.

The Mechanism of a Simple Drawing Operation. B. Fogg. (*Engineering*, 1954, **178**, Oct. 29, 551). Contrary to Professor Swift, the author claims to have found that the blank-holding force has a definite effect on the strain distribution in the critical regions of the drawn cup and shows the difference between the strains at the punch radius zone to be around 3% and at the rim around 7%. Lubrication in drawing operations is discussed.—M. D. J. B.

Processing and Drawing of Steel Wire. P. A. Beaman. (*Iron Steel Eng.*, 1954, **31**, Oct., 96–100). The author examines modern methods of wire drawing. Tungsten carbide and diamond dies are discussed together with methods of lubrication. Wire drawing machines of conventional and continuous types are described.—M. D. J. B.

Some Observations on Conditions of Lubricating in Wire Drawing Dies. D. G. Christopherson, N. Naylor, and J. Wells. (Symposium on Metal Working Oils: *J. Pet. Inst.*, 1954, **40**, Oct., 195–298). The results of experiments on the

establishment of fluid lubrication in a wire drawing die are described.—B. G. B.

Some Lubrication Effects in Deep Drawing Operations. E. M. Loxley and P. Freeman. (Symposium on Metal-Working Oils: *J. Pet. Inst.*, 1954, **40,** Oct., 299–307). The influence of lubrication on the stretch-forming and cylindrical drawing of steel sheet is discussed. Some effects of lubrication on the ironing of metal cups are reviewed and it is shown that, for optimum ironing conditions, it is desirable to employ a good quality lubricant between die and outer cup surface. In drawing operations optimum conditions result from using an efficient lubricant on the die side of the blank and no lubricant whatsoever on the punch side.

Study of Lubrication in Wire Drawing by an Electrical Method. A. E. Ranger and J. G. Wistreich. (Symposium on Metal-Working Oils: *J. Pet. Inst.*, 1954, **40,** Oct., 308–314). A description is given of the technique used and of the results obtained. Lubrication in wire drawing is shown to be intermediate between boundary and hydrodynamic.—B. G. B.

Lubricants for Tube and Bar Drawing. A. L. H. Perry. (Symposium on Metal-Working Oils: *J. Pet. Inst.*, 1954, **40,** Oct., 319–324). Various tube drawing processes are described and the requirements of a drawing lubricant are defined. Lubricants encountered in practice are tabulated. Reference is also made to bright bar drawing.—B. G. B.

Tube-Drawing Oils: The Function of Fatty and E.P. Additives. J. S. McFarlane and A. J. Wilson. (Symposium on Metal-Working Oils: *J. Pet. Inst.*, 1954, **40,** Oct., 324–331). The mechanism of the behaviour of these lubricants in tube drawing has been studied. A fuller understanding of the behaviour of lubricants in tube drawing can be obtained by a joint consideration of boundary friction and draw bench trials.—B. G. B.

Metal-Working Lubrication in the Bolt Industry. G. H. Townend. (Symposium on Metal-Working Oils: *J. Pet. Inst.*, 1954, **40,** Oct., 331–332). A brief account of present lubrication practice in the bolt industry is presented. Present practice is considered to be satisfactory.—B. G. B.

ROLLING-MILL PRACTICE

Steel Sections for Welding. R. G. Braithwaite. (*Brit. Welding J.*, 1954, **1,** Nov., 481–486). A brief history is given of rolling practice for the production of steel sections. The Gray Mill and other processes for broad flange beams are discussed. The attachment of the web to the flanges by continuous fillet welds is dealt with and compared with German methods in which the separately rolled flanges have raised 'nibs' in the centre, the object being to remove the weld away from the stress as far as possible. These flanges are known as the Dörnen, Krupp and Nase (nose) profiles.—R. A. R.

Forming Corrugated Sheet by Rolling. (*Engineering*, 1954, **178,** Nov. 5, 598–599). This article describes the largest corrugated sheet forming machine in England just completed by Joshua Bigwood and Son Ltd., Wolverhampton. The machine consists of 14 roll stands, each housing a pair of rolls mounted vertically one above the other and capable of forming 4000 12-ft. long sheets in one 8-hr. shift.—M. D. J. B.

Tandem Cold Mill Completes Rebuilding Programme at Allegheny Ludlum. (*Iron Steel Eng.*, 1954, **31,** Oct., 141–142). A description is given of the new four-stand mill at Allegheny Ludlum Steel Corp. which produces 48-in. wide coils of cold rolled electrical and stainless steels.—M. D. J. B.

Research on Pitting Strength under Rolling Contact. T. Nishihara and K. Endo. (*Kyoto Univ., Tech. Rep. Eng. Res. Inst.*, 1954, **(4),** Mar., Report No. 16, 1–26). [In English]. Tests are reported with steels heat-treated in various ways. The pitting limit is high with small-diameter rollers, and decreases to a fixed value as roller diameter increases. The increase in pitting limit due to small roller diameter is more marked with metals of small grain size. Pitting strength is slightly higher with viscous lubricants. Sliding added to rolling contact reduces pitting strength, and the effect of speed is explained. Except for very rough finishing, the pitting limit does not vary with surface finish.—K. E. J.

Temper Mill Control. G. P. Dirth. (*Iron Steel Eng.*, 1954, **31,** Oct., 81–92). The author gives a detailed description of temper mill controls and discusses schematic layouts, running procedure, variable voltage control, circuit details, and delivery and entry tension devices.—M. D. J. B.

The Roll-Setting Method of Automatic Control of Gauge in Hot and Cold Rolling Mills. R. B. Sims and K. H. Slack. (*Inst. Mech. Eng., Advance Copy*, Dec. 3, 1954). A closed-loop regulator has been constructed to demonstrate, on a pilot-plant scale, a method of automatically controlling the gauge of sheet and strip by hydraulic positioning of the rolls. Continuous measurements of roll-load and roll-setting indicate any departure from gauge, and correction is made by varying the position of the rolls. The controller is described together with experiments which demonstrate that the method is capable of consistent rolling to close tolerances.—P. M. C.

The Mechanism of Rolling Friction. D. Tabor. (*Phil. Mag.*, 1954, **45,** Oct., 1081–1084). It is shown that interfacial slip in most cases contributes very little to rolling resistance between metal surfaces covered with their usual oxide films. Lubricants can reduce metallic transfer but do little to reduce rolling resistance. The major part of the resistance arises from elastic hysteresis losses in the metals themselves. (12 references).—K. E. J.

Surface Friction and Lubrication in Cold Strip Rolling. P. W. Whitton and H. Ford. (*Inst. Mech. Eng., Advance Copy*, 1954, Nov. 15). A method is described for determining the friction coefficient in cold rolling by means of the equation $\mu = T/PR$, where T is the ratio torque/unit-width of roll, P is the ratio roll-force/unit-width, and R is the roll radius. The equation is valid only when the forward slip is zero or negative. Determinations were made of μ for mild steel, copper, brass, and aluminium, using a very wide range of lubricants. The results are tabulated and analysed. Values of roll force and torque calculated by using the values of μ in existing rolling theory show good agreement with measured values. (15 references).—P. M. C.

Surface Friction Investigations in Cold Rolling. P. W. Whitton. (*Australasian Eng.*, 1954, May 7, 54–62). Work carried out at Imperial College, London, is described whereby the mean coefficient of surface friction in cold rolling was obtained experimentally by making use of the equation $\mu = T/PR$ under conditions of zero or negative forward slip. (T = torque per unit width, P = roll force per unit width, R = roll radius). Values are tabulated for mild steel, copper, brass, and aluminium strip rolled with smooth rolls and a range of different lubricants. The results yielded were checked with and without back tension under the same lubrication conditions, and the measured roll force and torque was compared with values obtained using the derived friction coefficient in Bland and Ford's theory. Agreement between the two was within $\pm$ 5%.—P. M. C.

Lubrication of Strip in Cold Rolling Mills. R. B. Sims. (Symposium on Metal-Working Oils: *J. Pet. Inst.*, 1954, **40,** Oct., 314–319). The influence of friction on the forces required to deform cold rolled material is described and it is shown that changes in the frictional forces can cause appreciable variations in the gauge of the rolled product as the mill is accelerated and retarded. An explanation, supported by the results of rolling experiments, is suggested for this speed-variation effect.—B. G. B.

Seamless Tubes: A General Review of Current Shop Practice. D. E. Brooks. (*Iron Steel*, 1954, **27,** Sept., 459–461). The author briefly reviews present-day methods of producing steel for seamless tubes. He deals in turn with melting, refining and deoxidation practices, ingot casting, mould practice, 'hot-topping,' billet piercing by the Pilger mill, and tube straightening.—G. F.

Reliability in Industrial Electronic Equipment. E. D. Cook. (*Trans. Amer. Inst. Elec. Eng.*, 1953, Part I, **72,** 351–360). The reliability of width and thickness gauges in strip rolling mills, their maintenance, and the training of maintenance men are discussed.—R. A. R.

Accident Prevention in Rolling Mills: A. H. Daws. (*Iron Coal Trades Rev.*, 1954, **169,** Nov. 26, 1285–1286). Discussing accident prevention in rolling mills, the author considers regulations, records, and costs, and outlines an analysis of about 8000 accidents. The importance of full co-operation of foremen in the accident prevention policy is emphasized.

MACHINERY FOR IRON AND STEEL PLANT

The Economics of Replacement in the Steel Industry. G. G. Beard. (*Iron Steel Eng.*, 1954, **31,** Oct., 55–65). The author discusses the problem of replacement related to machinery and other production possibilities representing

major investments. The work of the Machinery and Allied Products Institute and their method of analysis are described in detail.—M. D. J. B.

Improvements on Forging Cranes. H. Ernst and K. Kleinschmidt. (*Iron Steel Inst., Translations Miscellaneous Series No.* 236, 1955). This is an English translation of a paper which appeared in *Stahl u. Eisen*, 1954, **74,** July 29, 1001–1008 (*see J. Iron Steel Inst.*, 1955, **179,** Feb., 193).

New 70-Ton Diesel Electric Shunting Locomotives in Use at Newcastle Steel Works. (*B.H.P. Review*, 1954, **31,** Sept., 10).

Design and Application of Conveyor Belts for the Steel Industry. D. R. Scheu. (*Iron Steel Eng.*, 1954, **31,** Oct., 117–122). The author discusses points to be considered when installing a conveyor belt scheme. The characteristics required for ore coal, coke, and steel scrap are described. Length limitations and general capabilities of belt systems are examined.—M. D. J. B.

LUBRICANTS AND LUBRICATION

Lubricating Oil Tests. A Survey of their Significance for Determining Quality. E. W. Steinitz. (*Automobile Eng.*, 1954, **44,** Sept., 375–378). The author briefly describes the significance of and methods for determination of specific gravity, ash content, carbon residue, cloud and pour point, viscosity, flash point, fire point, heat resistance, acidity, and oxidation of oils. The significance of such properties in relation to engine performance is discussed.—P. M. C.

Colloidal Molybdenum Disulphide. A Lubricant for Many Applications. F. G. Kay. (*Automobile Eng.*, 1954, **44,** Sept., 357, 358). Brief details are given of the excellent lubricating properties of colloidal molybdenum disulphide, and examples of its use in cutting operations, treatment of dies, thread rolling, assembly, running in of machines, and metal working are reviewed.—P. M. C.

Planned Lubrication at The Steel Company of Wales. IV. H. Barber. (*Sci. Lubrication*, 1954, **6,** Oct., 15–18). An account is given of the care and maintenance of the main lubricating oil systems serving the slabbing, continuous strip, temper and cold reduction mills. Features of interest are standardized operation, supervision and reporting, magnetic filters to collect the fine mill dust which passes the 0·008 in. gaps in the plate filters, centrifugal cleaners, and the periodic sampling system.—K. E. J.

Pumpability of Steel Mill Greases. J. S. Aarons and R. G. Warren. (*Iron Steel Eng.*, 1954, **31,** Oct. 67–72). The authors discuss the characteristics and properties of mill greases and stress the importance of 'pumpability,' i.e. the property which indicates how readily a grease can be moved in a lubricating system over a given temperature range.—M. D. J. B.

The Role of Friction in Metal Working Processes. H. Ford. (Symposium on Metal-Working Oils: *J. Pet. Inst.* 1954, **40,** Oct., 291–294). The present knowledge on the coefficient of friction in metal-working processes is examined and typical values are compared with those found in the usual slider tests. Recent experimental determinations of the coefficient for lubricated conditions in plane compression and cold rolling tests are described and the possible mechanism of friction is suggested.—B. G. B.

Practical Aspects of the Cold-Rolling of Narrow Steel Strip. T. W. Hood. (*J. Iron Steel Inst.*, 1955, **180,** June, 189–200). [This issue].

Silicone Oils for Lubricating Steel *versus* Steel. G. C. Gainer. (*Indust. Eng. Chem.*, 1954, **46,** Nov., 2355–2362). Silicone oils at present used have high thermal stability, a favourable viscosity-temperature relationship, high flash points and low freezing points, but compared with petroleum lubricants have high coefficients of friction and are poor lubricants between sliding ferrous surfaces under heavy load conditions. Incorporation in the silicone oil molecule of substitute phenyl groups in which the substituents are halogen atoms or halogen-containing groups, increases very considerably their load-bearing ability. The lubricating properties of these modified oils are compared with those of commercial silicone oils and other lubricants.—G. E. D.

WELDING AND FLAME-CUTTING

The British Welding Research Association. K. Winterton. (*Metallurgia*, 1954, **50,** Oct., 169–174). The activities of the engineering and metallurgical sections of this association during 1954 are discussed. A Baldwin-Tate-Emery 200-ton universal testing machine and a Sciaky 3-phase spot welding machine have been recently purchased.—B. G. B.

Automatic Argon Arc Welding of Low-Alloy Steel Sheet. F. J. Wilkinson. (*Brit. Welding J.*, 1954, **1,** Sept., 397–402). The author describes the fabrication of tubular components from low-alloy Cr–Mo steel sheet. The welding jigs and equipment are described and details of satisfactory welding technique are given. The occurrence of cracks and porosity constituted the major difficulties encountered, and the methods adopted to prevent the formation of these defects are indicated.—U. E.

The 'Twin-Argon' Welding Process. J. A. Donelan. (*Brit. Welding J.*, 1954, **1,** Sept., 403–408). Twin argon welding as an inert-gas shielded polyphase tungsten arc process has been developed for the high-speed mechanized welding of cable sheathing and metal tube manufacture. Arc phenomena, design features of the equipment, application, and metallurgical aspects are described.—U. E.

Energy Distribution in Argon-Shielded Welding Arcs. J. F. Lancaster. (*Brit. Welding J.*, 1954, **1,** Sept., 412–426). A mathematical treatment is given of energy distribution in argon-shielded welding arcs. Calorimetric measurements of the D.C. argon shielded tungsten-copper arc are reported, and values obtained for the anode and cathode potential drops. It is shown that the cathode potential drop is not associated with the ionization of excitation potential of the arc vapour and in fact is a dependent function which varies with the cathode heat loss.—U. E.

A New Process of Stud Welding. W. P. van den Blink, E. H. Ettema, P. C. van der Willigen. (*Brit. Welding J.*, 1954, **1,** Oct., 447–454: *Lastechniek*, 1955, **21,** Jan., 2–16). A new process of stud welding is described in which the timing is regulated by a cartridge on the end of the stud. A simple stud welding gun containing only a spring, pressing the stud holder on to the work piece, can be used.—U. E.

Welding of Carbon Steels by the Argonaut Process. H. F. Tremlett and A. W. Stones. (*Brit. Welding J.*, 1954, **1,** Dec., 541–548). Conditions for Argonaut welding semi-killed steel of boiler quality and fully killed steel of pressure vessel quality have been investigated. The production of consistently sound welds depends on filler wire quality and the efficiency of the argon shield. The process is suitable for metal deposition in all positions except the vertical; satisfactory weld soundness to radiographic standards was confirmed in downhand butt and horizontal and vertical fillet welds.—U. E.

Arc Weld Repairs on High-Speed Tool Steel. K. Rose. (*Mat. Methods*, 1954, **40,** Sept., 144, 145). Details are given of a technique for reclaiming worn and damaged high-speed steel tools by building up with a welding electrode containing 0·8–0·9% C, 3·75–4·25% Cr, 1·25–2·25% V, 3·75–5·50% Mo, 5·25–6·00% W, 7·50% min. Co, and 0·2–0·4% Mn. An argon shielded arc, using superimposed high frequency for stabilization, and a tungsten electrode, are employed.—P. M. C.

A Welding Procedure for Rail Joints. C. Hanappe. (*Brit. Welding J.*, 1954, **1,** Dec., 549–550). The welding of joints in rails by inserting a steel plate between the two faces to be joined is described and the metallurgical properties are discussed.—U. E.

The History, Development and Application of Low Hydrogen (Basic Coated) Electrodes. R. L. Gaughan. (*New Zealand Eng.*, 1954, **9,** June, 209–214). Compositions of organic, oxidizing, rutile, neutral and basic electrode coatings are tabulated and the purposes for which each type is used are discussed.—P. M. C.

Dry Hydrogen Brazing for High Strength Alloys. F. C. Kelley. (*Product Eng.*, 1954, **25,** Aug., 156–160). Materials such as stainless steels, Nichrome, silicon steels, and stellites are now being fabricated on a production basis by furnace brazing methods as a result of the development of pure dry hydrogen atmospheres. Brazing materials and joint designs are described. Joint strength can be high and corrosion resistance, oxidation resistance, and hardness are produced.

The Use of Resistance Welding in the Manufacture of Stainless-Steel Bellows. T. A. Dickinson. (*Sheet Metal Ind.*, 1954, **31,** Oct., 854, 855). The Circle Weld Co. Inc. at Burbank, California, has successfully developed methods for resistance welding stainless steel sheets with thicknesses ranging from 0·002 in. to 0·016 in. The welds in tubes for bellows manufacture are of a quality which will withstand

severe forming operations. Details of the equipment are not available, but currents of the order of 6000 amp. at only 1½ V. are required.—P. M. C.

Use of High Velocity Burners for Edge Heating Skelp. G. J. Campbell. (*Iron Steel Eng.*, 1954, **31,** Oct., 111–115). The author describes the welding installation used at Sparrow Point continuous butt weld pipe mills. Welding is accomplished after the skelp leaves the forming rolls, by means of a jet of air applied at the seam, which brings the two adjacent edges up to welding temperature before they pass into the welding rolls.—M. A. J. B.

The Properties and Uses of Metal Adhesives. R. A. Johnson. (*Sheet Metal Ind.*, 1954, **31,** Oct., 829–835, 841). Adhesive of the "Redux" (modified phenol-formaldehyde resin) and "Araldite" (epoxy group) types, which have found widespread uses, particularly in the aircraft industry, are considered. Fatigue strengths of lap joints made with such adhesives have much higher fatigue strength than riveted joints. The properties, applications, and curing techniques, are described. (12 references).—P. M. C.

MACHINING AND MACHINABILITY

A Theoretical Investigation of the Temperature Distribution in Metal Cutting Processes. A. C. Rapier. (*Brit. J. Appl. Phys.*, 1954, **5,** Nov., 400–405). The work material, the chip, and the machine tool have been considered as three separate problems for solution by relaxation and analytical methods in an ideal system. Comparison with other evidence is provided and modification of the mathematical treatment for incorporation of other data (e.g. change in thermal properties, yield stress etc.) is suggested.—J. O. L.

Some Aspects of the Metal Cutting Process. G. V. Stabler. (Symposium on Metal-Working Oils: *J. Pet. Inst.*, 1954, **40,** Sept., 256–260). The mechanism of metal cutting is reviewed, mention being made of plastic shear, build-up on the cutting tool edge, formation of cracks ahead of the tool, curvature of the chip, and power consumption.—B. G. B.

New Sulfur-Bearing Tool Steels—A New Materials Preview. (*Mat. Methods*, 1954, **40,** Sept., 96, 97). The improved service performance of tool steels with sulphur additions is briefly discussed. Five case histories are quoted which reveal more production with better surface finish from milling cutters and hobs made from sulphurized 6/6/2 Mo–W–V high-speed steel.—P. M. C.

Electrospark Machining. C. P. Porterfield. (*Steel Processing*, 1954, **40,** July, 443–446). Three basic methods of electromachining—viz. contact initiated discharge, and electrolytic and spark initiated discharge—are briefly described. Some electrical aspects of the process are discussed.—P. M. C.

Electric Spark Machining. The Sparcatron Process for Working Hard Materials. (*Automobile Eng.*, 1954, **44,** July, 295–297). Equipment for spark machining, manufactured by Impregnated Diamond Products Ltd., is described and illustrated. The principle of the method, viz. the removal of material by a succession of spark discharges between a shaped electrode and the workpiece (which is the other electrode) is described. Many applications are outlined.—P. M. C.

Developments in the Sparcatron Spark-Machining Process. (*Machinery*, 1954, **85,** Sept. 3, 488–492). Significant developments in connection with the "Sparcatron" technique for machining hard metals, whereby electrically conductive materials which cannot be machined with normal tools or readily ground by abrasive wheels, are discussed. The technique is now employed in the making and enlarging of wire extruding and blanking dies, and for the sinking of forging and stamping die forms.—M. A. K.

Mechanism of Friction and Lubrication in Metal-Working. F. P. Bowden and D. Tabor. (Symposium on Metal-Working Oils: *J. Pet. Inst.*, 1954, **40,** Sept., 243–253). The fundamental factors governing the lubrication and cutting of metals are considered and the results of experiments carried out using steel tools for cutting aluminium are described. When the cutting was carried out in H_2S gas or with a commercial sulphurized lubricant, a considerable improvement in surface finish was obtained over cutting in the absence of a lubricant.—B. G. B.

Chemical 'Milling.' (*Machinery*, 1954, **85,** Oct. 29, 907–916). A metal-removal process, which is based on chemical etching, has been developed by North American Aviation, Inc., Downey, California. It is claimed to afford substantial economies in the production of recessed and ribbed components.—M. A. K.

CLEANING AND PICKLING

Effluents in the Metal Finishing Industries. V. Evans. (*Metal Ind.*, 1954, **85,** Sept. 10, 211–214). Problems associated with the disposal of effluents and spent liquors are discussed, and methods of treatment before final discharge into rivers and sewers, are outlined under the headings: Acids; alkalis; metallic salts; chromic acid and chromates; and cyanides.—P. M. C.

Continuous Acid Regeneration.—A Description of a New Installation at a French Works. E. W. Mulcahy. (*Sheet Metal Ind.*, 1954, **31,** Oct., 850–853). This large regeneration system was designed by Chemical Engineering Construction (Pensett) Ltd., and runs on a continuous cycle in conjunction with a Wean continuous pickling installation. The output of the line is 10 to 20 tons/hr. of 80 in. wide strip, the pickle bath operating at 80 to 90° C. The plant embodies the rapid cooling principle, the final cooling temperature being −4° C. Waste acid composition is 300 g./l. copperas and 160 g./l acid.—P. M. C.

Push-Button-Controlled Rotary Coiled-Strip Pickling—Some Details of a New Installation. E. W. Mulcahy. (*Sheet Metal Ind.*, 1954, **31,** Sept., 738–739, 741). Brief details are given of a new installation, notable for its mechanization and automatic handling equipment. An average of 3 to 4 cages/hr. are dealt with irrespective of their loads. The consumptions of various materials per ton of strip pickled are: acid 50 lb. B.O.V. (brown oil of vitriol); steam 100 lb.; water 225 gal.; oil 2 gal.—P. M. C.

Metal Cleaning, with Special Reference to the Removal of Scale from Forgings. K. G. Lewis. (*Metal Treatment and Drop Forg.*, 1954, **21,** May 207–214; June 277–283; July, 335–342, 347; Aug., 377–386). The theory of scale formation and removal, its nature and controlling factors in practice, and the effects of furnace atmospheres are discussed. Chemical methods of descaling, including details of pickling techniques, baths used, solution control by inhibitors, and stainless steel pickling solutions are described. Details are also given of electrolytic and sodium hydride pickling methods. Finally, mechanical methods such as blast cleaning, shot peening, and liquid honing, are discussed and compared. (133 references).—P. M. C.

Review of Shot and Sand Blasting Plant. (*Product Finishing*, 1954, **7,** Sept., 79–89). A selection of equipment made by British manufacturers is described.—A. D. H.

PROTECTIVE COATINGS

Electrochemical and Electrometallurgical Industries. H. D. C. Rapson. (*Soc. Chem. Ind., Reports on Progress of Appl. Chem.*, 1953, **38,** 243–266). Recent developments in electrodeposition and metal finishing, the production of chemicals, extraction and refining, and the use of cells are reviewed. The subjects covered include equipment, waste disposal and electrolyte recovery, the preparation of metals for electroplating, the inspection of deposits, and the analysis of plating solutions.—J. E. J.

These Applications Take Advantage of the Properties of Ceramic-Coated Metals. B. W. King. (*Mat. Methods*, 1954, **40,** Oct., 104–106). Ceramic coatings on metal are hard and scratch resistant; they withstand a reasonable degree of thermal shock and exhibit excellent resistance to chemical corrosion and oxidation at elevated temperatures. The many applications in all spheres of industry and domestic life are briefly reviewed.—P. M. C.

Chelating Agents in Electroplating. C. D. Leonard. (*Electroplating*, 1954, **7,** Oct., 365–370). Chelating agents are sodium salts of ethylenediamine tetracetic acid. (E.D.T.A.) They can be used as sequestering agents to prevent the precipitation of calcium salts and also function as cleaning agents, for grease and oxides. In nickel plating they form stable complexes with impurities with copper and iron, and other applications are briefly mentioned, including a process for copper deposition by immersion and uses in volumetric analysis.—A. D. H.

Fire Hazards in Metal Finishing. (*Product Finishing*, 1954, **7,** Oct., 77–82). Fire hazards and methods of protection in cleaning, plating and painting processes are reviewed. Examples of recent conflagrations in the U.S. metal finishing industry are quoted.—A. D. H.

Chromium Diffusion as a Commercial Process. R. L. Samuel and N. A. Lockington. (*Indust. Finishing*, 1954, **6**, July, 896–910). Chromium diffusion is a new process, used to prevent corrosion, heat, and wear resistance. Details are given of the D.A.L. process, which uses chromium iodide in a box treatment, and is applicable to sheets, rods, bars, and large and small articles. Applications are described. Although further development work is necessary, the process has become established, not as a substitute for plating or stainless steel, but more as an intermediate finishing process, particularly when further mechanical processing is involved.

Application of Galvanizing to Engineering Problems. W. B. Dunn. (*New Zealand Eng.*, 1954, **9**, Aug. 15, 267–274). This article provides engineers with a useful working knowledge of the process of galvanizing, and information on expected life, quality control, and design. The testing and inspection of galvanized coatings, and their serviceability in various climates and atmospheres, are discussed, and they are compared with other forms of metal protection.—P. M. C.

'White Rust.' Some Comments on Its Significance in Relation to Inspection of Galvanized Articles. H. Bablik. (*Sheet Metal Ind.*, 1954, **31**, Oct., 845, 846). It is emphasized that the appearance of "white rust" (zinc carbonate and hydroxide) is not always a sufficient reason for rejection of galvanized articles. Actual corrosion may be only very slight. Dipping in sodium bichromate solution will inhibit its formation.—P. M. C.

The Electrodeposition and Protective Value of Zinc-Cadmium Alloys. N. I. Kudryavtsev and E. F. Pereturina. (*Zhurnal Prikladnoy Khimii*, 1953, **26**, (2), 155–159: *Electroplating*, 1954, **7**, Oct., 372—375). Cyanide-base electrolytes were used with 50/50 Zn–Cd anodes to determine the value of the deposits for the protection of steel in marine environments. Compositions of electrolytes and electrolysis conditions were established for the deposition of Zn–Cd alloys of a range of compositions. An alloy containing 17–20% Zn gave the best protection and behaved similarly to pure cadmium in the salt spray test.—A. D. H.

The Recovery of Zinc from Dross. A. G. Thomson. (*Metallurgia*, 1954, **50**, Oct., 159–160). The economic aspect of various methods which have been suggested for the recovery of zinc from large or small quantities of dross is discussed.

Laboratory-Scale Simulation of the Electro-Tinplate Manufacturing Process. R. Mills and C. J. Thwaites. (*Sheet Metal Ind.*, 1954, **31**, Sept., 733–737). The essential feature of the industrial electrolytic tinning process is the high speed of the strip through the electrolyte, which causes appreciable agitation. In order to simulate this movement in the laboratory, and that the process might be studied under controlled conditions, a circulating electrolytic cell was constructed and is described in detail. Samples of electrotinplate $10\frac{1}{2}$ in. × $3\frac{1}{2}$ in. can be produced. An apparatus for flow brightening using electrical resistance heating is also described and illustrated.—P. M. C.

Tin-Nickel Alloy Plating—A New Decorative and Protective Coating. (*Automobile Eng.*, 1954, **44**, Aug., 320–322). A recently developed process for the electro-deposition of 65/35 tin–nickel alloy is described. The alloy is harder and more resistant to corrosive media than either of its constituents. A copper base is normally necessary for application of the coating. Details are given of equipment, anodes, and process control.—P. M. C.

Silicone in Protective Coatings. M. A. Glaser. (*Indust. Eng. Chem.*, 1954, **46**, Nov., 2334–2342). The increasing application of silicone polymers in the protective coatings industry is discussed. At present, the major uses are in the design of heat, weather, and corrosion resistant coatings for a variety of articles and equipment.—G. E. D.

The Protective Properties of Various Phosphate Coatings on Steel. J. F. Andrew, S. G. Clarke, and E. E. Longhurst. (*J. Appl. Chem.*, 1954, **4**, Nov., 581–595). Coatings of iron, manganese, and zinc phosphates formed on steel by representative industrial immersion processes are compared, with special reference to their value in the prevention of rusting, in the light of the thickness, composition, and wear resistance of the coatings. Protective properties are fairly well developed in manganese phosphate coatings, but iron and zinc phosphates can give adequate results in appropriate systems. A recent spot test of Russian origin, suitably modified, is likely to provide a useful additional tool for examining coatings.

J. O. L.

Methods of Studying the Thermal Resistance of Sprayed and Electro-Deposited Metal Coatings. R. W. Powell and M. J. Hickman. (*Brit. J. Appl. Phys.*, 1954, **5**, Sept., 312–315). The use of a thermopile and of a modified divided bar method for investigating the increased thermal resistance produced by a sprayed or electro-deposited metal-on-metal coating is described. The former can be used to determine the surface temperature of unground specimens, the latter only on flat surfaces; however, the divided bar method also provides information about the the thermal bond between the metal surface. The thermal conductivity of sprayed steel was about one-seventh that of the solid metal.—J. O. L.

An Instrument for Measuring the Chip Resistance of Paints. E. P. Brightwell. (*Amer. Soc. Test. Mat. Bull.*, 1954, Sept., 53–55). The instrument described is suitable for measuring the relative resistance of paint films to chipping.—B. G. B.

POWDER METALLURGY

Sintering. C. G. Paulson. (*Metal Progress*, 1954, **66**, Nov., 122–123, 176). The use of controlled gas atmospheres during the sintering of powdered metal compacts is described. The type of furnaces used is also considered briefly.—B. G. B.

Chromium-Nickel Alloy Steel Powders for High Strength Parts. E. Gordon, W. V. Knopp, and J. D. Shaw. (*Mat. Methods*, 1954, **40**, Oct., 107–109). Pre-alloyed chromium-nickel powders can now be added to inexpensive reduced iron powders, to produce strong and wear-resistant sintered products. Exploratory experiments are reviewed in which 50/50 and 80/20 Cr–Ni alloy powders were studied, and the properties of a range of sintered compacts are reviewed.

Sintering Metal Powder Compacts. P. F. Hancock. (*Metal Ind.*, 1954, **85**, Sept. 17, 225–228). The author describes and illustrates furnaces designed for continuous sintering. Sintering atmospheres (hydrogen, cracked ammonia, endothermic, and exothermic atmospheres) are discussed, and details are given of temperatures and procedures for sintering copper-base and iron-base materials, and carbides.—P. M. C.

PROPERTIES AND TESTS

Modern Ideas About Properties of Metals. W. E. Boas. (Australian Inst. Metals: *Australasian Eng.*, 1954, Apr. 7, 57–61). A brief review is presented of recent outstanding developments connected with electrical resistivity and plastic deformation. The author outlines the main features of the free electron theory, Brillouin zones, and the theory of dislocations.—P. M. C.

Acceptance Tests in the Steel Industry: What is Really Wanted? J. M. Mowat. (*West of Scotland Iron Steel Inst., Advance Copy No.* 476: *Iron Coal Trades Rev.*, 1954, **169**, Dec. 24, 1505–1509). The author considers some of the tests carried out to determine the suitability of a steel to meet service conditions, and assesses their importance and value. He asks for early consultation between designer and steelmaker, so that a proper specification can be prepared to satisfy all requirements in the simplest and safest manner.—G. F.

Treatment of Tension Test Specimens for Fixing in Testing Machines. H. Krenchel. (*Amer. Soc. Test. Mat. Bull.*, 1954, Sept., 44–46). The treatment of the ends of specimens to be held in the jaws of testing machines in static and fatigue tests with plastic resins prevents the slip of specimens during testing. Cold setting ethoxylene resins have been used with satisfaction.—B. G. B.

Plane Frame for Testing Structures. J. C. Chapman and S. R. Sparkes. (*Engineer*, 1954, **198**, Nov. 12, 654–655). A description is given of an internally equilibrated two-dimensional testing frame in use at Imperial College. The frame is designed to apply loads up to 100 tons. Structures with overall dimensions up to 22 ft. by 8 ft. can be tested.

Determining the 'True' Elastic Limit by a Bend Test under Tension. E. Mohr. (*Forsch. Ingenieurwesens*, 1953, **19**, (2), 33–43). If a test piece in the form of a strip of sheet metal under tension is bent over rollers backwards and forwards through a small angle, the curve of tensile stress against number of reversals to fracture shows a characteristic point of inflection. The stress at this point corresponds to the 'true' or 'natural' elastic limit defined by Bauschinger. Under appropriate testing conditions, this test gives a value agreeing closely with the fatigue limit of the material, and has the advantage that it is quicker to carry out. It is also useful for examining the effect on the fatigue limit of notches or welds.—H. R. M.

Experiments on the Effect of Rate of Testing on the Criterion of Failure of Certain Mild Steels. N. G. Calvert. (*Inst. Mech. Eng., Advance Copy*, Jan. 7, 1955, 9–12). Torsional impact tests have been carried out on 0·12, 0·19 and 0·31% carbon steels subjected in addition to various intensities of axial tensile stress up to 16·8 tons/sq. in. Yield stresses at low and high torsional speeds are compared with those predicted by various criteria of failure. Increased speed of testing moves the criterion of yield away from that of constant shear strain energy towards that of constant maximum tensile stress. The maximum torsional stresses lie between the constant maximum shear and tensile stresses and are apparently unaffected by straining rate.—P. M. C.

Impact Torsion Experiments. N. G. Calvert. (*Inst. Mech. Eng., Advance Copy*, Jan. 7, 1955, 3–8). A machine is described by means of which complete torque-time curves for impulsive torsional fracture may be determined. Results for 0·12, 0·19, and 0·31% carbon steels show that, while the maximum stresses do not differ appreciably from the static values, the yield point is greater when the straining rate is high (about 60 radians/sec.). Further experiments at lower speeds (4 radians/sec. and less) show that both upper and lower yield points increase progressively with straining rate, and, for the steels tested, a transition from static to impact conditions is suggested at a straining rate of about 0·1 radian/sec. or less. (12 references).—P. M. C.

Influence of Deuteron Bombardment and Strain Hardening on Notch Sensitivity of Mild Steel. R. A. Meyer. (*J. Appl. Phys.*, 1954, **25,** Nov., 1369–1374). Deuteron bombardment (at 18·6 MeV) affects the impact resisting properties of mild steel in a similar manner to strain hardening, but apparently by the formation of interstitial vacancies. The effect is mainly local, increasing non-linearly with depth of penetration, and recovery is achieved by annealing at between 260° and 480° C., the activation energy increasing meanwhile.

Stress Measurement by X-Ray Diffraction. H. T. Letner and S. R. Maloof. (*J. Appl. Phys.*, 1954, **25,** Nov., 1440). Surface stresses with steep gradients normal to the surface can be calculated from X-ray deflection measurements using a weighted average of the stress concentration in various sub-surface layers. If the gradient is small, X-ray diffraction gives comparable results and it is demonstrated that mechanical values of elastic constants cannot be used in the X-ray stress equation.—J. O. L.

Effects of Residual Stresses in Welded Structures. G. M. Boyd. (*Brit. Welding J.*, 1954, **1,** Dec., 560–566). A review is given of published data on the effects of residual stresses in welded mild steel structures. It seems probable that the detrimental effects generally attributed to residual stresses are in fact due to metallurgical changes which in the presence of stresses may lead to fracture and that the beneficial effects of stress relieving are due to improvement of the metallurgical structure.—U. E.

Strain Determination by Brittle Coating. T. Nishihara, S. Taira, and H. Maeda. (*Kyoto Univ., Tech. Rep. Eng. Res. Inst.*, 1953, Dec., Report No. 14, 1–28). [In English]. To simplify stress analysis, the use of a brittle paint containing phenolic resin and TiO_2 can be used to indicate strain, eosin dye being used to clarify the crack pattern. The method has been analysed theoretically and practically; it is simple, convenient and capable of quantitative results.—K. E. J.

Examining the Quality of Photoelastic Materials. R. Hiltscher. (*Forsch. Ingenieurwesens*, 1954, **20,** (3), 66–76). Proposals are made for standard test procedures for comparing materials on the basis of stress-optical effect, deviation from proportionality, optical creep, and edge effect.

The Effect of Fluid Pressure on the Shear Properties of Metals. B. Crossland. (*Inst. Mech. Eng., Preprint*, Oct. 15, 1954). An apparatus is described in which it is possible to carry out torsion tests under fluid pressure up to 20 tons/sq. in., and up to 40 tons/sq. in. if another torque bar is used. A simple high pressure intensifier and secondary pressure gauge are also described. The results show that pressure has no significant effect on the shape of the stress-strain curves of mild steel, copper, silicon-aluminium alloy, zinc, and a zinc-aluminium alloy, though it does increase the strain to failure of the first three linearly with pressure. (19 references).—P. M. C.

Operating Data for the Murex Hot Crack Testing Machine. E. C. Rollason and D. F. I. Roberts. (*Brit. Welding J.*, 1954, **1,** Oct., 441–446). The detailed application of the Murex type of hot crack testing machine is described and information is given on the practical significance of the results with mild and stainless steel electrode deposits. An inexpensive pattern suitable for a workshop test machine has been tested and is briefly described.—U. E.

Inspection, Explosion and Breakdown of Boilers and Pressure Vessels. J. Eyers. (*Inst. Mech. Eng., Advance Copy*, Nov. 12, 1954). Some causes and the prevention of failures in boilers, steam generating plant, and pressure vessels are analysed and discussed with reference to actual case histories. Among the causes of failure dealt with are corrosion fatigue and defective welding.—P. M. C.

Why Parts Fail. J. A. Bennett and G. W. Quick. (*Product Eng.*, 1954, **25,** Aug., 129–134). Twelve examples are given of the failure of parts under service conditions. Common types of failure are: Static and overload fractures, fatigue fractures, and stress corrosion cracking. Causes of failure may be the use of the wrong material, decarburization that reduces strength, or fretting between parts. Also included are some precautions that should be considered in the design, fabrication, and use of metal parts to reduce service failures.

Failure and Survival in Fatigue. A. M. Freudenthal and E. J. Gumbel. (*J. Appl. Phys.*, 1954, **25,** Nov., 1435). The introduction of an " auxiliary survivorship function " enables true fatigue limits to be determined even when several specimens under test survive a known finite number of stress applications.—J. O. L.

Residual Stresses in Metals and Metal Construction. W. R. Osgood [editor]. (New York, 1954: Reinhold Publishing Corporation). This 363-page monograph consists of papers which, taken together, summarize and assess the present state of knowledge on the effects of residual stresses upon the performance of structures, with particular emphasis on the contributions of these stresses to fracture. The monograph was prepared for the Ship Structure Committee under the direction of the Committee on Residual Stresses of the National Academy of Sciences and the National Research Council. It contains the following papers:

Effect of Residual Stresses on the Behaviour of Structures. F. Campus. (1–21).

Residual Stresses in Welded Pressure-Vessel Manufacture. H. Harris. (23–32).

Some Typical Cases Where Residual Stresses Set Up by Welding Appear to Have Contributed to Ship Structural Failures. D. Arnott. (33–39).

Residual Stresses As a Factor in Ship Fractures. Admiralty Ship Welding Committee. (41–44).

Some Notes on Typical Residual Stresses Encountered in Welded Ships. P. Ffield. (45–74).

Some Considerations Regarding the Generation and Importance of Residual Welding Stresses. L. E. Benson. (75–83).

Residual Stresses in Welding. W. Sparagen. (85–102).

The Significance of Residual Stresses. C. W. MacGregor. (103–126).

Some Remarks on the Influence of Residual Stresses on the Brittle, Plastic, and Fatigue Behaviour of Structures. P. P. Bijlaard. (127–138).

The Influence of Residual Stresses on the Behaviour of Ductile Structures. M. R. Horne. (139–161).

Shakedown of Elastic-Plastic Structures. P. G. Hodge, jun. (163–185).

The Inclusion of Initial Residual Stresses in Hodge's Elementary Example and a Numerical Illustration. W. R. Osgood. (186–191).

Microstresses Originated by Gas Inclusions. N. J. Petch. (193–199).

The Effect of Residual Stresses on High-Speed Impact Resistance. J. Miklowitz. (201–217).

Correlation of Residual Stresses with Fatigue Strength of Machine Elements and Related Phenomena. O. J. Horger and H. R. Neifert. (219–253).

Effect of Residual Stress on the Failure of Engineering Materials. D. Rosenthal. (255–269).

Measurement of Residual Stress. D. Rosenthal. (271–283).

Residual Stresses Associated with Lattice Strains. G. B. Greenough. (285–296).

Precautions to be Used in the Measurement and Interpretation of Residual Stresses by X-Ray Technique. W. S. Hyler and L. R. Jackson. (297–303).

Complete Determination of the State of Residual Stress in Solid and Hollow Metal Cylinders. H. Bühler. (305–329).

Determination of Residual Stresses Below the Surface. W. Soete and R. Vancrombrugge. (331–334).

Effects of Residual Stress on Fatigue Life of Metals. R. L. Mattson. (*S.A.E. Trans.*, 1954, **62**, 416–425). Experimental analyses of residual stresses as related to fatigue properties and to the surface failure known as spalling are discussed. The contributions of heat-treatment, machining, grinding, and straightening to residual stress formation are outlined, and practical methods of measurement of such stresses are described.—P. M. C.

Effect of Temperature on Endurance Limit and Relaxation of Spring Materials. F. P. Zimmerli and W. P. Wood. (*S.A.E. Trans.*, 1954, **62**, 557–565). Details are given of experiments undertaken to determine endurance limits and load losses at temperatures from − 75° to 650° F. for a range of different spring materials. The tests were conducted on helical springs both shot peened and unpeened. Shot-peened springs had higher endurance limits and greater relaxation than unpeened springs at − 75° and + 75° F., but as test temperatures were raised the endurance limits of all unpeened springs tended to remain steady whilst that of peened springs tended to decrease.—P. M. C.

A Fatigue Testing Machine for Range of Stress. J. P. Romualdi, C. L. Chang, and C. F. Peck, jun. (*Amer. Soc. Test. Mat. Bull.*, 1954, Sept., 39–43). A study of the effect of range of stress on the fatigue properties of rotating beam specimens has been made. The fatigue testing machine employed enables a range of loading from pure tension to pure bending in any combination to be applied to the specimen.

Basic Concepts of Fatigue Damage in Metals. T. J. Dolan. ('*Fatigue*': *Amer. Soc. Met. Educational Lectures*, 35th National Metal Congress, Oct. 19–23, 1953, 1–35). The nature of fatigue failures in metals is considered in order to clarify the available information upon which future predictions concerning the life of metal parts may be based. Fatigue is defined as progressive fracture and its general mechanism is briefly discussed. The levels of observation used in fatigue studies are classified as visual observation of large-scale phenomena, microscopical or X-ray observations of microscopic or submicroscopic phenomena, and imaginative reconstruction of atomic behaviour. The influence of microstructure on fatigue strength is discussed at length.

Fatigue Failure under Resonant Vibrating Conditions. B. J. Lazan. ('*Fatigue*': *Amer. Soc. Met. Educational Lectures*, 35th National Metal Congress, Oct. 19–23, 1953, 36–76). Resonance as a cause of fatigue failure and the relative importance of fatigue strength and damping capacity are discussed. The nature of resonant vibration and its amplification of fatigue stress are considered with reference to damping. The sources of damping are classified as external and internal and their relationship to stress is discussed. The importance of considering damping capacity in conjunction with fatigue strength when selecting resonant strength materials is stressed, particularly when the internal damping plays a significant part in total damping. The resonant strength is found to be affected by a material factor as defined by its resonant strength constant, and a part factor as defined by its volume-stress factor K_V.—J. E. J.

Fatigue Characteristics of Large Sections. O. J. Horger. ('*Fatigue*': *Amer. Soc. Met. Educational Lectures*, 35th National Metal Congress, Oct. 19–23, 1953, 77–118). Previous work on the effect of specimen size on fatigue strength of small sections is reviewed, and work carried out on statistical effects is summarized. The mode of testing and the test results are described for a number of studies carried out on large diameter specimens. These include 6 and 8·5 in. dia. plain specimens, 5·5 in. dia. fillet specimens, 9·75 in. marine shafting, 9·65 and 6·5 in. dia. crankshafts, and large diameter welded tubing.—J. E. J.

Reproducibility of Wöhler-type Fatigue Tests. J. Clayton-Cave, R. J. Taylor, and E. Ineson. (*J. Iron Steel Inst.*, 1955, **180**, June, 161–169). [This issue].

Dislocations, Fatigue and Fracture. N. F. Mott. (*Proc. Royal Inst. Great Britain*, 1954, **35**, Part 3 (160), 666–669). The author shows from his own and other work that fatigue cracks are initiated in zones where a cluster of strong slip lines appear together. Such a series of lines appear, on examination with the optical microscope, to be one line which slowly broadens during the fatigue life, but the electron microscope has shown them to be, in fact, a cluster. The author suggests that each elementary line of slip has small cracks at its extremities, thus weakening the material progressively until visible cracking becomes apparent.

Hardness of Metals and Alloys. G. P. Chatterjee. (*Indian J. Phys.*, 1954, **28**, Jan., 9–20). An attempt has been made define hardness H as the work done per unit volume of indentation in a static ball indentation test. A simplified equation $H = afn$ is derived, where a and n are constants and fn is a known function of n, and H (expressed as kg-mm./cu. mm.) is shown to compare well with H_B (Brinell). Advantages and limitations of this method of definition are discussed.—J. O. L.

The Role of Hardenability in the Choice of Structural Steels. A. Rabinovicz. (*Schweiz. Arch. Wiss. Techn.*, 1954, **20**, Apr., 110–119). [In French]. Methods of measuring hardenability of steels, and the use of Jominy hardenability test data to find the depth of complete hardening in pieces of different size, are described. The available evidence on the extent to which steels of different composition, hardened to the same degree, differ in their other mechanical properties, is presented, and the reasons for the difference between American and European practice in the use of alloying materials are discussed. The introduction of quantitative measures of hardenability would allow the metallurgist to offer the engineer more economical steels better adapted to their conditions of service.—H. R. M.

The Relation between Hardness and Tensile Tests. A. Braun. (*Schweiz. Arch. Wiss. Techn.*, 1954, **20**, Feb., 56–58). [In German]. From analogies between hardness and tensile tests, a theory is advanced to explain the variation of hardness number with load in terms of elasticity, strain hardening, and heterogeneity. It is concluded that hardness testing can show properties of the material not readily demonstrated by the tensile test.—H. R. M.

Optical Aid for the Determination of Microhardness. H. Schulz. (*Schweiz. Arch. Wiss. Techn.*, 1954, **20**, Jan., 24–29). [In German]. This article deals with the principles of design of microscopes for the measurement of microhardness impressions, with special reference to magnification, field of view and brightness, taking into account the characteristics of the average human eye.—H. R. M.

Diamond Indentors for Rockwell-Hardness Testing. F. R. Tolman and Joyce F. Hall. (*Engineering*, 1954, **178**, Dec. 10, 760–762). Developments at the National Physical Laboratory in the measurement of the angle of the cone and the radius of the tip of diamond indentors for Rockwell hardness tests are described and details of experience gained in the inspection of indentors during the past few years are reported.

The Physical Meaning of Indentation Hardness. D. Tabor. (*Sheet Metal Ind.*, 1954, **31**, Sept., 749–757). The hardness of metals is discussed in terms of their resistance to local plastic deformation. The empirical formulæ for hardness numbers in terms of yield strength are studied for the different shapes of indenters used in Vickers, Brinell, and Rockwell tests. The effect of work-hardening on hardness values, Meyer's law, and the relation between indentation hardness and ultimate tensile strength are discussed.—P. M. C.

Effect of Annealing Condition on Hardness and Structure of High-Carbon Steel Strips. II. Y. Fukao. (*Tetsu to Hagane*, 1954, **40**, Aug., 761–765). [In Japanese]. Results are reported for four samples annealed and cold-rolled to various degrees of reduction. With increase of reduction, the recrystallization temperature fell, the hardness was raised (except near the recrystallization temperature), and carbide spheroidization became more uniform. Hardness was reduced with slow rates of cooling from above the transformation temperature. It is concluded that the annealing range must be narrow for hot-rolled strip, though it is not so critical for cold-rolled strip.—K. E. J.

Practical Application of the Reichert Micro-Hardness Tester. E. M. Onitsch-Modl. (*Sheet Metal Ind.*, 1954, **31**, Oct., 867–870). A brief description is given of the construction and working principle of the Reichert microhardness tester, and several examples of the application of microhardness testing are discussed. (16 references).—P. M. C.

Age-Hardenable Metals. J. L. Everhart. (*Mat. Methods*, 1954, **40**, Oct., 121–136). The author discusses the possibilities of precipitation or age hardening, the temperature ranges required, and the mechanical properties which can be developed in light metals, heavy non-ferrous metals, irons and

steels, and super alloys. The A.S.T.M. definitions of various different ageing treatments and precipitation and solution treatments are quoted. In the section dealing with irons and steels, treatments and properties for high-alloy Cr–Ni stainless types, Nitralloy, and low-alloy tool steels are discussed.

The Strain Ageing of Alpha-Iron. W. R. Thomas and G. M. Leak. (*J. Iron Steel Inst.*, 1955, **180**, June, 155–161). [This issue].

Temper Embrittlement of 5140 Steel. S. H. Bush and C. A. Siebert. (*Trans. Amer. Inst. Min. Met. Eng.*, 1954, **200**: *J. Met.*, 1954, **6**, Nov., 1269–1271). Isothermal temper embrittlement studies have been made on A.I.S.I. 5140 steel (0·84% Cr, 0·43% C) at various temperatures and periods up to 3000 hr., the specimens being subjected to impact tests, metallographic examination, and hardness and lattice parameter measurements. The results are discussed and the effects of the various treatments on the degree of embrittlement are described.—G. F.

Increase of Initial Permeability of Low Alloy Iron-Silicon and Iron-Aluminium Alloys by Oxidizing Annealing at Low Temperature. H. Fahlenbach and E. Houdremont. (*Iron Steel Inst. Translations Miscellaneous Series, No.* 234). This is an English translation of a paper which appeared in *Arch. Eisenhüttenw.*, 1954, **25**, July-Aug., 377–381 (*see J. Iron Steel Inst.*, 1955, **179**, Mar., 300).

The Change of Ferromagnetic Curie Points with Hydrostatic Pressure. L. Patrick. (*Phys. Rev.*, 1954, **93**, Feb. 1, 384–392). The effect of pressure on the Curie temperature has been measured for 13 ferromagnetic materials, comprising iron, cobalt, nickel, gadolinium, seven alloys, and a perovskite. Curie points ranged from 16° C. (for Gd) to 1120° C. (for Co), and pressures up to 9000 atm. The results disagree with two common forms of the interaction curve. The result obtained for iron did not agree with Kornetzki's prediction.—R. A. R.

The Influence of Pressure on the Curie Temperature of Iron and Nickel. R. Smoluchowski. (*Phys. Rev.*, 1954, **93**, Feb. 1, 392–393). A comparison is made between Patrick's measurement of the change of Curie temperature under pressure, and theory based on a Brillouin function. The agreement is fair.—R. A. R.

The Permeability of Silicon-Iron at Very Low Flux Densities. E. Both. (*Trans. Amer. Inst. Elec. Eng.*, 1953, Part I, **72**, 656–664). Results are presented and discussed of determinations of permeability of sheets of 3·25% Si steel after annealing in hydrogen at various temperatures. Results indicate that silicon steel can replace nickel–iron alloys for many applications in telecommunications.—R. A. R.

Contribution to the Theory of the Coercive Force of Steel. E. Kondorskii. (*Doklady Akademii Nauk S.S.S.R.*, 1948, **63**, (5), 507–510). [In Russian]. The effect of inclusions on the critical field and the coercive force is discussed. The distinction between ferromagnetic materials containing fine and coarse inclusions is shown and formulæ for the critical field for these two cases are derived. Good agreement between experimental data and results calculated with the formulæ is claimed.—V. G.

Determination of Heat Capacity by Pulse Heating. T. E. Pochapsky. (*Rev. Sci. Instruments*, 1954, **25**, Mar., 238–242). The theory, construction and application are given of an apparatus for measuring the heat capacity of metal wires by pulsed heating.—L. D. H.

An Estimation of Some Unknown Surface Tensions for Metals. J. W. Taylor. (*Metallurgia*, 1954, **50**, Oct., 161–165). The surface tensions of 27 metals have been estimated where experimental data are lacking. The metals include iron, cobalt, manganese, molybdenum, and vanadium.—B. G. B.

High-Voltage X-Ray Generators for Industrial Radiography. (*Engineer*, 1954, **198**, Dec. 10, 827–828). This article describes high-voltage X-ray equipment developed by the Massachusetts Institute of Technology and manufactured by the High Voltage Engineering Corp. of Cambridge, Mass. The equipment described combines the characteristics of penetration, speed, spot size, and field coverage. A 14 in. by 17 in. radiographic film can be completely covered in one exposure at a target-to-film distance of 40 in.—M. D. J. B.

Radioactivity in the Foundry. A. K. Robinson. (*Foundry and Metal Treating*, 1954, **1**, Apr., 7–9, 12–16). After a brief outline of the structure of the atom and the origin of beta, gamma, and X-rays, the author discusses radioactive isotopes and the types of radiation emitted by them. The radiographic examination of castings is then dealt with, illustrations being given of several types of defect. Tracer techniques, as applied to slag-metal reaction studies, are also described. A list of radioisotopes giving half-life and type of radiation is presented.—P. M. C.

Iron and Steel. B. R. Davidson, R. W. Nichols, and C. J. Leadbeater. (*Soc. Chem. Ind., Reports on Progress of Appl. Chem.*, 1953, **38**, 171–193). Developments in the physical metallurgy of ferrous metals during 1953 are reviewed. The subjects dealt with include: Constructional and engineering steels, high-temperature steels, corrosion-resistant steels, magnetic materials, low-temperature properties and brittle fracture, temper-brittleness, hydrogen embrittlement, ageing effects in low-carbon steels and the manufacture and properties of powders for powder metallurgy.—J. E. J.

New Super-High Strength Structural Steels. A. E. Nehrenberg. (*Mat. Methods*, 1954, **40**, Oct., 100–103). The compositions, treatments, and properties of new steels developed to improve the strength/weight ratio of aircraft components are discussed. Among these are HY-Tuf, Super HY-Tuf and High Carbon Super HY-Tuf, which can be treated to tensile strengths of 230,000, 294,000, and 325,000 lb./sq. in. respectively, and still exhibit appreciable toughness. These steels, developed by the Crucible Steel Co. of America, contain from 0·25–0·47% C., 1·50–2·42% Si, and balanced amounts of nickel, chromium, molybdenum, vanadium and manganese.—P. M. C.

High Tensile Steels. J. Apraiz. (*Bol. Min. Ind.*, 1954, **33**, May, 269–277). [In Spanish]. The compositions of 11 low-alloy steels made by S. A. Echevarria, Bilbao, are given and their properties are discussed. These steels have tensile strengths in the 60–170 kg./mm. range. The carbon is about 0·30% and they are alloyed with various combinations of chromium, nickel, molybdenum, and vanadium.—R. A. R.

Steels for High Pressure Plants in the Chemical Industry. I. Class. (*Werkstoffe u. Korrosion*, 1954, **5**, Aug.-Sept., 281–285: Iron Steel Inst., Translations Miscellaneous Series 130). A review is presented of German experience of the use of low-alloy and high-alloy steels in plant for high-pressure chemical synthesis. The effects of hydrogen attack and of high alternating stresses are among the subjects considered.—J. C. H.

The Safety Factor in the Design of Seamless Steel Gas Cylinders. S. E. Mitchell. (*Metallurgia*, 1954, **50**, Aug., 87–89). The merits of several methods which are in use for the application of a safety factor are discussed and a common basis for deriving the working stress is proposed.

Use of Steel in Constructional Work. (*Iron Coal Trades Rev.*, 1954, **169**, Nov. 26, 1279–1281). A summary is given of the 16th International Congress of Steel Information Centres, held to discuss the advantages of high-tensile steel for constructional work, with special reference to plates and sheets. Their use in Italy, France, Belgium, Switzerland, and Great Britain is described, and economic aspects are surveyed.—G. F.

Notch Ductility of Nodular Irons. G. A. Sandoz, H. F. Bishop, and W. S. Pellini. (*Foundry*, 1954, **82**, Sept., 114–119, 263–266). The notch brittleness of cast iron is briefly discussed and Charpy **V**-notch transition curves for some nodular irons are presented and compared with the results obtained by the Naval Research Laboratory drop weight test. In this test, plates supported at both ends and with a brittle weld bead notched by an abrasive wheel in one face, are tested at different temperatures by dropping a weight on to the opposite face. Stops prevent the plate from bending more than 5° and the highest temperature at which this deformation is sufficient to produce a completely brittle fracture, is taken as the transition temperature. Results to show the effects of composition and microstructure on transition temperature are presented. Silicon, phosphorus, and pearlite plus free carbide all raise this temperature. The effects are additive and may be represented by an empirical formula. The application of the results of the drop weight test to service performance and to design are discussed.

METALLOGRAPHY

Photometry of the Microscope with Special Reference to Projection. F. E. J. Ockenden. (*J. Sci., Instruments*, 1954, **31**, Sept., 309–313). The transmission lines in microscope optical systems are related to the calculation of the limiting illumination of projected images.—L. D. H.

A New Reflecting Spectrograph Camera. C. Moser. (*J. Opt. Soc. Amer.*, 1954, **44**, Aug., 660–663). The camera which has been developed consists of a spherical mirror and a corrector lens with spherical surfaces. The equivalent focal length is about 900 mm. and the relative aperture is *f*4. The design is based on the theory by Argentieri and becomes a camera of the non-concentric type. The useful range of the camera is from 2500Å. to 12,000Å. Some details of the construction and results obtained are shown.

Automatic Pole Figure Recorder. A. H. Geisler. (*Rev. Sci. Instruments*, 1954, **25**, Aug., 727–732). With this apparatus, pole figure data as supplied from a Geiger Counter X-ray diffraction apparatus are recorded directly in stereoscopic projection.—L. D. H.

Concentration Contours in Grain Boundary Diffusion. R. T. P. Whittle. (*Phil. Mag.*, 1954, **45**, Dec., 1225–1236). Mathematical formulæ are obtained for the concentration in a poorly diffusing half space bisected by a thin well-diffusing slab, at different times after the edge of the half-space has been suddenly raised from zero to unit concentration. This represents a simplified model for studying grain boundary diffusion, and has applications to heat flow in a poor conductor with a metallic fin.—K. E. J.

The Discovery of X-ray Diffraction by Crystals. Sir Lawrence Bragg. (*Proc. Royal Inst. Great Britain*, 1954, **35**, Part 3, (160), 552–559). The author describes the steps leading to the discovery by von Laue of the diffraction of X-rays by crystals and some of the early work subsequently carried out on crystal structure by the author.—J. E. J.

Lattice Imperfections and Plastic Deformation in Metals. I—Nature and Characteristics of Lattice Imperfections, Notably Dislocations. II—Behaviour of Lattice Imperfections During Deformation. H. G. van Bueren. (*Philips Tech. Rev.*, 1954, **15**, Feb.-Mar., 246–257; Apr., 286–295). In Part I the theoretical necessity for the existence of lattice imperfections in crystals, such as vacancies, interstitial atoms and dislocations, is clarified in the light of phenomena related to the plastic deformation of metals, *e.g.*, the occurrence of slip lines, work hardening, and variations in the electrical conductivity. The author discusses some characteristics of dislocations, and deals with the geometrical aspects of the various types, their behaviour under shear stresses, and their modes of movement, taking into account the difference between conservative and non-conservative movements. The formation of lattice defects of different kinds as the outcome of interaction between existing defects is examined. Part II deals with the effects of imperfections on certain mechanical properties; the mechanism of slip during plastic deformation is discussed with reference to microscopic observations. (37 references).—P. M. C.

Inclusions in Iron Crystals Obtained by Recrystallization. T. Smith. (*Acta Met.*, 1954, **2**, Sept., 647–654). [In English]. Small iron crystals (' inclusions ') in a coarser grained matrix were produced by the strain-anneal method. Most inclusions were shown by X-ray crystallography to be exact twins of the larger crystals, but some of the four twin orientations are missing. The twins are assumed to originate by faulting on the {112} planes during recrystallization.—A. D. H.

On Self-Diffusion in Cubic Metals. F. S. Buffington and M. Cohen. (*Acta Met.*, 1954, **2**, Sept., 660–666). [In English]. A method based on the vacancy mechanism of diffusion is given for calculating activation energies (Q_M) of self-diffusion in cubic metals. It is shown that Q_M is proportional to an elastic constant and the cube of the lattice parameter, both referred to 0° K. Reasonable agreement is found with recent self-diffusion measurements. Values are given for the fraction of the activation energy that goes into lattice straining during diffusion for face-centred-cubic metals but for body-centred-cubic metals data are inadequate. The above quantities permit the calculation of the self-diffusion coefficients of cubic metals.—A. D. H.

An X-Ray Diffraction Method for the Study of Substructure of Crystals. J. Intrater and S. Weissmann. (*Acta Crystallographica*, 1954, **7**, Nov. 10, 729–732).

Moduli and Internal Friction of Magnetite As Affected by the Low-Temperature Transformation. M. E. Fine and Nancy T. Kenney. (*Phys. Rev.*, 1954, **94**, June 15, 1573–1576). The low-temperature ordering transformation in magnetite is the source of large non-elastic effects. For example, Young's modulus for the <111> direction at 108° K. is 30% lower than the value estimated from high-temperature measurements; an internal friction peak occurs near 95° K. The authors have attributed the non-elastic effects to stress-induced ordering of Fe^{2+} and Fe^{3+} among the octahedral sites in the lattice.—R. A. R.

Magnetic Resonance in α-Fe_2O_3. P. W. Anderson, F. R. Merritt, J. P. Remeika, and W. A. Yager. (*Phys. Rev.*, 1954, **93**, Feb. 15, 717–718). Magnetic resonance of α-Fe_2O_3 confirms the existence of highly anisotropic, weak ferromagnetism which disappears below — 15° C. The energy/orientation relationship has been studied.—J. O. L.

Neutron Diffraction Study of the Anisotropy Transition in α-Fe_2O_3. L. M. Corliss, J. M. Hastings, and J. E. Goldman. (*Phys. Rev.*, 1954, **93**, Feb. 15, 893–894). The change in magnetic behaviour of α-Fe_2O_3 at sub-zero temperatures owing to anisotropic transition is shown to occur at a temperature governed by the characteristics of the crystal examined.—J. O. L.

On Secondary Hardening in a Chromium–Molybdenum Steel. L. Habraken. (*Rev. Mét.*, 1954, **51**, Aug., 541–550). The secondary hardening of a 2·25%-Cr 1%-Mo steel has been studied. Two stages were noted, the first due to transformation of austenite to ferrite and carbide, the second to the formation of a special carbide. A preliminary examination of this phase has been made using X-ray and electron metallographic methods. The heat-treatments capable of inducing such hardening are indicated.—A. G.

Contribution to the Study of the Electrolytic Extraction of Carbides from High Speed Steel. J. Papier. (*Rev. Mét.*, 1954, **51**, Oct., 723–734). The amount of carbide dissolved increases with the temperature of austenite formation and particularly between 1100° and 1200° C. Chemical analyses shows these carbides to be high in tungsten (60%) and vanadium with a chromium content below that of the steel. The chromium content of the matrix remains constant as the austenitizing temperature falls from 1300° to 900° C. Whilst the carbon, tungsten, and vanadium contents decrease considerably.

A Geiger Counter X-Ray Crystal Spectrometer. P. J. A. McKeown and A. R. Ubbelohde. (*J. Sci. Instruments*, 1954, **31**, Sept., 321–326). Details are given of the design, construction and applications of a Geiger-Müller X-ray spectrometer suitable for measuring transitions in single crystals.

Stabilization of the Bainite Reactions. R. F. Hehemann and A. R. Troiano. (*Trans. Amer. Inst. Min. Met. Eng.*, 1954, **200**: *J. Met.*, 1954, **6**, Nov., 1272–1280). The influence of partial decomposition to high-temperature bainite on reaction kinetics at a low temperature has been studied in two 0·3–0·4% C steels containing 1·79% Ni, 0·81% Cr, 0·26% Mo and 3·07% Ni, 1·22% Cr, 0·49% Mo, respectively. Reaction at the lower temperature is retarded by the previous treatment, and the extent of decomposition may be reduced. Interpretation of the results is based on a mechanism involving a limitation in the nucleation and growth of bainite plates.

Isothermal Transformation of Austenite in the Pearlite Range from the Carburizing Temperature. H. M. Meingast. (*Durferrit Hausmitteilungen*, 1952, (25), 5–44). The heat-treatment of carburized steel parts is discussed with special reference to the differences in the transformation of austenite from centre to surface of the part.—R. A. R.

Transformation Temperature of Alloy Steels Related to Weldability with Low-Hydrogen Electrodes. C. L. M. Cottrell. (*Brit. Welding J.*, 1954, **1**, Sept., 409–412). The liability of certain low-alloy Mn–Ni–Cr–Mo steels to hard zone cracking when arc-welded with a low-hydrogen electrode has been related to the temperature for completion of austenite transformation during cooling. The progress of transformation has been studied using a rapid action dilatometer in which the thermal cycle which occurs adjacent to a given weld was imitated, the relative efficiencies of the alloying elements carbon, manganese, nickel, and chromium have been observed and results expressed as proof-stress/weldability ratios.—U. E.

Atomic Interaction in Molten Alloy Steels. J. Chipman. (*J. Iron Steel Inst.*, 1955, **180**, June, 97–106). [This issue].

A New Iron Boro-Carbide. K. G. Carroll, L. S. Darken, E. W. Filer and L. Zwell. (*Nature*, 1954, **174**, Nov. 20, 978–979). X-ray studies of the system Fe-C-B revealed the existence of a new boro-carbide with a complex carbide structure and the suggested formula $Fe_{23}(C, B)_6$. This is claimed to be the first reported case in which another element (boron) has replaced carbon in this structure. These

experiments may shed some light on the pronounced effect of boron on the hardening properties of steel.—G. E. D.

Investigation of Ferrochrome-Silicon. N. N. Kurnakov. (*Izvestiya Sektora Fiziko-Khimicheskogo Analiza*, 1949, **17**, 209–219). The Cr–Fe–Si ternary system in the region of 30–70% Si and 10·25% Fe was investigated using thermal analysis and microstructural examinations. The presence of (Cr,Fe)Si and (Cr,Fe)Si_2 phases was confirmed. Alloys containing 25–42% Si and 0·06–0·08% C contain primary precipitates of characteristic carbide needles which transform into carbide precipitates of various shapes as the carbon increases to 0·10%. In the presence of 42–60% Si no carbide precipitation was found.—V. C.

Effect of Carbon Content in the 500° F. Embrittlement of Tempered Martensite. P. Payson. (*Trans. Amer. Inst. Min. Met. Eng.*, 1954, **200**,: *J. Met.*, 1954, **6**, Nov., 1242–1243). From a series of **V**-notch Charpy impact tests, the author concludes that tempered martensite is embrittled during the third stage of tempering regardless of composition, which affects only the transition temperature. The embrittlement is also independent of the quantity of the freshly formed cementite.—G. F.

Effect of Nitrogen on Sigma Formation in Cr-Ni Steels at 1200° F. (650° C.). G. F. Tisinai, J. K. Stanley, and C. H. Samans. (*Trans. Amer. Inst. Min. Met. Eng.*, 1954, **200**: *J. Met.*, 1954, **6**, Nov., 1259–1267). The authors have studied the effect of nitrogen additions on the location of the $(\gamma + \sigma)/\gamma$ and the $(\gamma + \alpha + \sigma)/(\gamma + \alpha)$ phase boundaries in the ternary Fe–Cr–Ni system, for cast and wrought alloys of simulated commercial purity, and in similar alloys with silicon additions up to 2½%. Nitrogen additions of 0·10–0·20% cause a real displacement of the phase boundaries towards higher chromium contents, and nullify the opposing effect of 1% Si at all nickel levels from 8 to 20%. At the lower nickel level, the effect of 2% Si is also nullified. The rate of σ formation is discussed.—G. F.

The Determination of the Ms Temperature by Dilatometric Method. H. Nishimura and T. Mitani. (*Kyoto Univ. Memoirs Faculty Eng.*, 1954, **16**, Jan., 1–8). [In English]. A new method is described, employing sensitive dilatometric analysis, based on the primary shrinkage brought about by the change of martensite to tempered martensite in the martempered steel on heating.—K. E. J.

CORROSION

Corrosion of Metals. S. C. Britton. (*Soc. Chem. Ind., Reports on Progress of Appl. Chem.*, 1953, **38**, 232–242). Progress in the field of corrosion during 1953 is reviewed. Experimental methods, high-temperature corrosion, atmospheric corrosion, corrosion in soil and water, microbiological corrosion, and stress corrosion are discussed. (134 references).—J. E. J.

Nomographs for Making Corrosion Rate Calculations. W. A. Szymanski. (*Corrosion*, 1954, **10**, Dec., 422–424).

Stress Corrosion of 12% Cr Stainless Steel. W. L. Badger. (*S.A.E. Trans.*, 1954, **62**, 307–310). Stress corrosion cracking in compressor rotor blades made from type 403 stainless steel is discussed. Experiments are described in which specimens were flexed in a jig and immersed in a solution of HCl plus 1% SeO_2. Since tensile stresses of approximately 50,000 lb./sq. in., were required to cause corrosion cracks, it was concluded that residual stresses in the leading edge of the blades was the cause of the trouble. Stress relieving at 950° F. was found to be a successful remedy.—P. M. C.

Electrical Measurements in the Selection of Bolt Materials for Service Underground. W. J. Schwerdtfeger. (*J. Res. Nat. Bur. Stan.*, 1954, **52**, May, 265–274). Electr cal measurements made in the laboratory are useful in generally predicting the relative behaviour of bolt materials in resisting corrosion underground. Some arbitrarily chosen low-alloy ferrous materials are shown to be superior to plain cast iron or steel commonly used for the fabrication of bolts. The effect of exposure on the potentials of cast iron and galvanized iron as components of galvanic couples is described.—R. A. R.

Ships and Rust. J. Getz. (*Tekn. Ukeblad*, 1954, **101**, Oct. 21, 823–830, Oct. 28, 855–861). [In Norwegian]. This detailed review of the problem of marine corrosion and its prevention deals with: Corrosion mechanism, concentration cells, stress corrosion, welded and riveted joints, surface pretreatment by pickling, sand-blasting, and flame cleaning. Correct procedure and conditions required during painting are outlined.—G. G. K.

Testing of Materials for Naval Shipboard Sea Water Carrying Systems. J. W. Jenkins and J. B. Guerry. (*J. Amer. Soc. Naval Eng.*, 1954, **66**, Aug., 607–639). A description is given of the activities of the corrosion laboratory of the U.S. Navy at Harbour Island and Kure Beach, North Carolina. A wide range of materials has been tested for the resistance to corrosion and the results obtained are given.—B. G. B.

Control of Corrosion in Underground Pipelines. H. L. Hamilton. (*J. Amer. Water Works Assoc.*, 1954, **46**, Oct., 1021–1024). A brief account of the corrosion of underground pipes by stray direct electric currents, corrosive soils, heterogeneous nature of the structural materials, and anaerobatic sulphate-reducing bacteria is presented.—B. G. B.

Prevention of Corrosion in Steel Wagons. (*Railway Gaz.*, 1954, **101**, Oct. 8, 409–410). A short illustrated account of methods used by British Railways for descaling and protective painting of all-steel wagons is given.—B. G. B.

Maintenance Aspects of Corrosion Program at Fairless Works. K. L. Johannsen. (*Iron Steel Eng.*, 1954, **31**, Sept., 115–121). Stray-current, galvanic, and local-cell corrosion are explained and the maintenance programme at the Fairless Works of the U.S. Steel Corp. is described. This programme has three main purposes: (1) To discover stray D.C. currents when they occur, and eliminate them; (2) to determine anode life by test data so that replacements are made in good time; and (3) to obtain test data for use in designing future anti-corrosion installations.—R. A. R.

Oxidation of Plain, Alloyed, and Ductile Irons at 1300 Degrees F. J. A. Cameron. (*Corrosion*, 1954, **10**, Sept., 295–298). Ordinary flake graphite cast iron, ductile iron, and high-alloy cast irons containing both flake and spheroidal graphite were subjected to oxidation tests in a furnace with circulating air. The tests, which were made on 4 × 1 × ¾ in. specimens heated to 1300° F. for up to 4000 hr., indicate that ductile irons are markedly more resistant to oxidation than flake graphite irons in these conditions.—J. F. S.

Radiometric Study of Phosphate Coatings Formed on Steel in Pretreatment Baths. T. F. Boyd, M. Galan, and L. Markowitz. (*Corrosion*, 1954, **10**, Sept., 285–288). The amount of phosphate coating formed on steel by various processes was investigated by measuring the radioactivity of radiophosphorus. The corrosion resistance of the coatings was tested by repeated washings with distilled water. No correlation was found between the amount of phosphate coating formed and the corrosion resistance. The most resistant coatings were formed by diammonium-phosphate/sodium-nitrite and sodium-phosphate/sodium-nitrite treatments, the least by phosphoric acid alone.—J. F. S.

The Corrosive Nature of Combustion Gases. G. Whittingham. (*Corrosion Techn.*, 1954, **1**, Aug., 182–187, 193). An outline is given of the laboratory and field investigations on corrosion by flue gases from solid fuel combustion carried out by the British Coal Utilisation Res. Assoc. The effects of different flue gas constituents on corrosion phenomena are discussed. Laboratory studies of the effects of fuel type and method of combustion on the sulphuric acid content of combustion gases are described. The results of measurements of the condensation characteristics of flue gases from water-tube boilers and furnaces are presented, and investigations into the use of additives are briefly described. (28 references).

The Mechanism of the Corrosion-Inhibitive Action of Paints, with Special Reference to Basic Pigments. J. E. O. Mayne and D. van Rooyen. (*J. Appl. Chem.*, 1954, **4**, July, 384–394). Chromatographic and other analyses of water-extracts from linseed-oil base metal soaps, which are non-corrosive to iron and steel, have shown the presence of various organic acids and their metal salts. Synthetic mixtures have been made exhibiting similar properties, and tests on isolated compounds (over the working range, *p*H 4·6–5·0) have indicated their relative contribution to the inhibitive effect, which is theoretically explained.—J. O. L.

Selecting Gaskets to Limit Corrosion of Stainless Steel Bolted Joints in a Chemical Plant. E. V. Kunkel. (*Corrosion* 1954, **10**, Aug., 260–266). Examples are described of corrosion of austenitic stainless steel joint surfaces caused by liquids penetrating the gaskets. Liquids of high electrical conductivity containing weak oxidizing or reducing agents were the principal cause of pitting. Chlorides in the gasket materials may have contributed to stress corrosion cracking. Tests showed that gasket materials should be fibre-less or have fibre-free surfaces.—J. F. S.

Cathodic Protection of Steel-Piled Wharves. L. T. Ryan. (*J. Inst. Eng. Australia*, 1954, **26**, July-Aug., 160–168). The author discusses the mechanism of corrosion and of cathodic protection. This is followed by a description of the design of the installation used. Future trends in design are considered. Cathodic protection is considered superior to coatings under water.—R. P.

The Prevention of Corrosion in Storage Tanks for Petroleum Products. H. B. Footner. (*Schweiz. Arch. Wiss. Techn.*, 1954, **20**, Mar., 72–75). [In German]. Methods of corrosion protection, with special reference to the practice of the Shell group, are described. Plates are prepared by pickling and phosphate treatment. The outsides of tanks are given two coats of lead paint and two of aluminium paint. A 2-in. thick bitumen and sand bed is formed below the base. Buried tanks are covered with a 5-mm. coat of bitumen or pitch, and often given a further cathodic protection by the use of magnesium anodes.—H. R. M.

Valves to Combat Corrosion. (*Chem. Eng.*, 1954, **61**, Sept., 198–204). Seventy-five questions and answers that will help in the selection of suitable corrosion-resistant materials for valves for various purposes, are quoted.—D. E. D.

Corrosion Problems in Phosphoric Acid Manufacture. J. J. Porter and G. C. Lowrison. (*Indust. Chem.*, 1954, **30**, Aug., 369–373). The authors discuss the behaviour of various materials in the production of phosphoric acid. Sulphuric acid storage tanks and feeders are made of mild steel. Two types of low-molybdenum steel are considered suitable; the carbon content must be low; stabilization with titanium or niobium presents no remedy for high carbon content.—R. P.

New Metal Corrosion Inhibitor. (*Chem. Age*, 1954, **71**, Dec. 4, 1183–1184). Laboratory tests show that cyclohexylamine carbonate is more efficient as a corrosion inhibitor than dicyclohexylamine nitrite. The former also arrests the progress of corrosion once it has set in. It is more effective in the vapour phase. Results of small-scale tests on mild steel, cast iron, and some non-ferrous metals are given.

A Promising Spray-Applied Inhibitor of Internal Corrosion of Oil Tank Ships. J. D. Sudbury, D. A. Shock, and F. W. Mann. (*Corrosion*, 1954, **10**, Aug., 253–258). The seriousness of internal corrosion of tanker compartments is discussed and present methods of protection reviewed. Laboratory experiments are described which have led to shipboard trials of a spray-applied inhibitor containing calcium sulphonate and sodium sulphonate with rosin amine stearate as a tackifying agent. The hydrocarbon carrier has too high a flash point. It is concluded that: (1) A suitable laboratory system has been established for the evaluation of spray treatments for use in cargo tanks or other petroleum storage facilities. (2) Test coupons are an adequate measure of corrosivity when carefully used. (3) Spray systems such as are normally used in Butterworthing are suitable for applying the inhibitor. (4) Chemical formulations developed have greatly reduced corrosion in the cargo compartments of oil tankers.—J. F. S.

Corrosion and Deposit in Gas Turbines. B. O. Buckland. (*Indust. Eng. Chem.*, 1954, **46**, Oct., 2163–2166). The ash from residual fuels used in gas turbines is often very corrosive to high temperature turbine parts. Vanadium and sodium are two of the most corrosive ash constituents, the effects of which have been mitigated as a result of tests carried out by the General Electric Company. Modified fuel specifications are put forward.—G. E. D.

Some Observations of Cathodic Protection Potential Criteria in Localized Pitting. (*Corrosion*, 1954, **10**, Aug., 232–236). Potentials of anode and cathode were measured in a model cell which included the basic spatial, electrical and environmental factors found in localized pitting, using two media of specific resistivity 160 ohm-cm. and 15,000–22,000 ohm-cm. Equipotential lines determined in the corroding media were plotted both in open circuit and when protective current was applied and corrosion current flow from the pit had stopped. The equipotential line corresponding to the open circuit potential of the anode is some distance from the cathode. Measurements with the D.C. null potential technique were used to investigate the relationship between the corrosion current and breaks in the potential log-current curve. It was observed that: (1) Potential measurements of a protected structure should include all the *IR* drop resulting from the flow of current through the resistance due to cathode surface and catholyte. The smaller the anode, the closer the reference electrode should be to the structure. (2) The ratio of protective current required to corrosion current increases with increasing media resistivity. (3) Mill scale can be more noble than copper.—J. F. S.

Corrosion by and Deterioration of Glycol and Glycol-Amine Solutions. W. G. Lloyd and F. C. Taylor, jun. (*Indust. Eng. Chem.*, 1954, **46**, Nov., 2407–2411).

Corrosion Inhibitors and Polarographic Maxima. H. C. Gatos. (*J. Electrochem. Soc.*, 1954, **101**, Sept., 433–441). Similarities are shown to exist between corrosion and polarographic processes. Results for polarographic studies on corrosion inhibitors used with an Fe/H_2SO_4 system showed that the inhibitors suppress one or more of the oxygen, lead, or nickel polarographic maxima. The mechanism of inhibition is discussed.—A. D. H.

ANALYSIS

Determination of Carbon and Sulfur in Ferrous Metals. A. C. Holler, Rosemary Klinkenberg, C. Friedman, and W. K. Aites. (*Analy. Chem.*, 1954, **26**, Oct., 1658–1661). A combined method for determining both carbon and sulphur is described in which a single weighed sample and a Lindberg H.F. combustion furnace are used. The gases from the combustion of the metal in oxygen are passed first through an absorption-titration vessel for absorption of SO_2, and then, after removal of moisture, over Ascarite to absorb CO_2. The carbon is then determined gravimetrically, and the sulphur, acidimetrically, or iodometrically. Results on many samples are quoted.—T. E. D.

Rapid Photometric Determination of Chromium in Alloy Steels and Bronzes. M. D. Kahn and F. J. Moyer. (*Analy. Chem.*, 1954, **26**, Aug., 1371–1373). A method suitable for 0·5–10% Cr in bronze alloys, 8–30% Cr in steels, and 0·5–15% Cr in alloy cast irons is described. The chromium in solution is oxidized by perchloric acid, then reduced with metallic zinc to produce an aqua-colour complex which is photometrically analysed at 585 mμ. Interference by copper, molybdenum, and especially nickel are considered. Good reproducibility and speed are obtainable.—T. E. D.

A Short History of Spectroscopy. I—The Early Days of Spectroscopy. II—Exploration of the Ultra-Violet and Infra-Red Regions. III—The Theory of the Prism. IV—The Theory of the Diffraction Grating. V—The Theory of the Interferometer. VI—Limits of Transparency. VII—Selective Reflection. VIII—Stefan's Law of Total Radiation. IX—Measurement of Energy Distribution in the Spectrum. X—Energy Distribution in the Spectrum. T. W. Chalmers. (*Engineer*, 1953, **196**, Aug. 7, 166–170; Aug. 14, 194–195 Aug. 21, 226–227; Aug. 28, 258–260; Sept. 4, 290–291; Sept. 11, 328–329; Sept. 18, 359–360; Sept. 25, 386–387; Oct. 2, 418–419; Oct. 9, 450–451).

The Mass Spectrometer as an Analytical Instrument. G. P. Barnard. (*Analyst*, 1954, **79**, Oct., 594–607). A brief description is given of some modern instruments, and techniques. Application of the method to the anlysis of stainless steel is described. The material to be analysed forms one electrode of the high voltage spark gap. Results are quoted, and the method is discussed.—T. E. D.

ECONOMICS AND STATISTICS

The Mineral Production of India and Burma During 1939. C. S. Fox. (*Rec. Geol. Sur. India*, 1953, **78**, Part 3, 301–405).

The Mineral Production of the Indian Union During 1948. W. D. West. (*Rec. Geol. Sur. India*, 1952, **82**, Part 3, 359–529).

The Mineral Production of the Indian Union During the Year 1950. M. S. Krishnan. (*Rec. Geol. Sur. India*, 1953, **84**, Part 2, 237–302).

MISCELLANEOUS

The British Iron and Steel Research Association. (*Metallurgia*, 1954, **50**, Oct., 176–180). A short survey of the work of B.I.S.R.A. during 1954 is presented. The projects considered include the cooling of blast-furnace hearths, sintering, continuous casting, open-hearth burner design, lubrication in wire drawing, stretcher strain markings, corrosion of low alloy steels, and special iron ore wagons.—B. G. B.

Training in the Iron and Steel Industry. A. W. W. Watson. (*J. Iron Steel Inst.*, 1955, **180**, June, 169–175). [This issue].

COLOMBIER, L., and J. HOCHMANN. "*Aciers Inoxydables, Aciers Réfractoires.*" Preface de H. Malcor. La. 8vo, pp. x + 526. Illustrated. Paris, 1955: Dunod. (Price 4750 fr.)

This book gives a vast amount of data on the rust-, acid-, and heat-resisting steels, and it is surprising how much information the authors have managed to get into the 526 pages. There are chapters on the mechanical and chemical properties of the steels and others which give information regarding the melting, manipulation, heat-treatment, machining, welding and descaling, as well as some review of the theories of corrosion, scaling, and creep.

The book is to a large extent a review of existing literature, and it is inevitable that some selection has had to be made from the vast amount available. Nevertheless, omissons of importance are few and there is little which calls for serious criticism. The chapter on scaling is particularly good. The following comments may, however, be made.

Intercrystalline corrosion of the carbide-precipitation type is reviewed in detail, but no mention is made of selective attack associated with sigma or other phase effects. The error is perpetuated of calling the acid copper sulphate test for intercrystalline corrosion either the Moneypenny or the Strauss test, whereas it should be now well known that this test was originated by the late Dr. W. H. Hatfield.

Although five pages are devoted to atmospheric corrosion mainly from American sources, no mention is made of the more recent and more comparative work of Shirley and Truman (*Journal of The Iron and Steel Institute*, Dec., 1948).

The chapter on high creep-resisting alloys is perhaps the most disappointing. Only two British steels are mentioned, and these are not typical of present-day practice.

The book is well written and can easily be read and understood by anyone with no more than a schoolboy knowledge of French. It deserves and will command a circulation outside the French-speaking countries.

J. WOOLMAN.

ERDMANN-JESNITZER, FRIEDRICH (Editor). "*Werkstoff und Schweissung.*" Handbuch für die Werkstoff- und werkstoffbedingte Verfahrungstechnik der Schweissung. Band II. La. 8vo, pp. xvii + 1005–1619. Illustrated. Berlin, 1954: Akademie-Verlag. (Price DM 40.–)

This is the second volume of an encyclopædic treatise, of which the first volume—published in 1951 and reviewed in these columns in March, 1952—dealt with weldability and welding processes, with special welding problems and with selected aspects of the subject for treatment in great detail.

This volume begins as a continuation of Part I of the whole work dealing with ferrous metals, and contains sections on the selection of the most economical welding methods for certain types of joint; distortion and shrinkage as affected by welding procedure (in sharp contrast with the other sections this one has only a single bibliographical reference); jigs for welding and especially automatic welding; building up by welding; the lining of vessels and pipe-jointing by welding and some repair problems; welding in shipbuilding; and the welding of cast iron. This completes the purely ferrous section of the work.

A long section on non-destructive testing comes next; it covers radiography, the effect of defects on the strength of joints, and the magnetic-powder and ultrasonic methods of flaw detection, but the use of radio-active isotopes for radiography is hardly mentioned, since this chapter was apparently written in 1950—this may be due to the difficulty of synchronizing the work of the two dozen or so contributors to the book.

The second half of the volume deals with the welding of non-ferrous metals: Copper and its alloys, nickel, zinc, lead, tungsten, molybdenum, tantalum, niobium (columbium)—but not titanium—gold, silver, platinum, and the light metals and their alloys. An unexpected section of 30 pages discusses the manufacture of aluminium alloys from the viewpoint of their weldability, but it is much too long; three pages would have sufficed, because the details do not concern the welding engineer.

The Editor appears to have had difficulty in excising irrelevant matter from some of the contributions, in ensuring the inclusion of all relevant facts and in maintaining a proper balance. Thus, the corrosion of welds runs to nearly 40 pages, whilst mechanical testing is confined to 14; again, butt-welded aluminium chains and their strength properties are discussed fully, but the size of the links is not mentioned. The excessive detail given about the manufacture of aluminium alloys has been mentioned already. For a subject index we shall presumably have to wait for Volume III, but the table of contents of this volume does occupy eleven pages.—E. VAN SOMEREN.

GRAY, CHARLES S., LEWIS E. KENT, W. A. MITCHELL, and G. BERNARD GODFREY. "*Steel Designers' Manual.*" Prepared for the British Steel Producers' Conference in conjunction with the British Iron and Steel Federation. La. 8vo, pp. vii + 909. Illustrated. London, 1955: Crosby Lockwood and Son, Ltd. (Price 50*s.*).

In this book of about 900 pages a great quantity of everyday structural engineering information has been gathered together. It is not a text book, since it makes no attempt to prove the hundreds of formulæ it contains; nor is it just a handbook, since it gives much more than bare facts and is particularly rich in examples of how the various formulæ are used. It is in fact a cross between the two which enables the designer to arrive quickly at the answers to most of his problems. Formerly a large collection of reference books was required for this purpose.

The authors have covered as broad a field as the title allows; for, in addition to the information one would expect, such as the stress analysis of frames and the design of structural joints, there are notes on such divers subjects as overhead gantry cranes and railway clearances. In one chapter is given a very useful collection of influence lines for continuous beams and redundant frames. Other chapters deal with flat plates, bunker design, torsion, plastic theory, foundations, side cladding and glazing, and many other subjects.

Perhaps the greatest weakness of the book is its index. It has many major omissions and is poorly arranged. For example, a table giving bulk densities of crushed rock and other materials is not referred to in the index under "Weights," "Bulk Densities" or "Densities"; it is found only under the heading "Bunkers." Another weakness is the lack of references; there are few, if any, footnotes, and bibliographies appear after only a few chapters.

Nevertheless, this manual is a very valuable source of information and will enable many short cuts to be made by those connected with the design of structures. Although it refers mainly to steel, it does, of course, contain much general information which makes it useful to those who design in other materials.—P. M. WORTHINGTON.

HALL, A. M. "*Nickel in Iron and Steel.*" (Alloys of Iron Research New Monograph Series.) 8vo, pp. xii + 595. Illustrated. New York, 1954: John Wiley and Sons, Inc.; London: Chapman & Hall, Ltd. (Price 80*s.*)

The first monograph dealing with some of the alloys of iron and nickel and prepared under the auspices of the Engineering Foundation of the U.S.A. was published in 1938, and covered a number of special purpose alloys. In 1942 when the work of the Alloys of Iron Research was suspended for World War II, the manuscript for the second volume was about 75% completed, but during the four years that the research was dormant, great strides were made in metallurgy, with the result that much of the original manuscript for volume 2 with its mass of tabular and graphical data had become obsolete. The committee of the Engineering Foundation were hence very wise in deciding to postpone publication until the book had been brought up to date, and the result is this excellent second volume entitled "Nickel in Iron and Steel."

The book is divided into 15 chapters, which adequately cover all aspects of the melting and working of nickel-alloy steels, the principles and practice of the metallography and heat-treatment of wrought nickel steels, room-temperature tensile properties of quenched and tempered wrought nickel steels, effect of temperature on the mechanical properties of nickel steels, the corrosion of low-alloy steels and cast irons containing nickel, cast steels containing nickel, the history, constitution, structure and manufacture of cast irons containing nickel, and their mechanical properties. It concludes with an excellent bibliography of 784 references and adequate name and subject indexes.

It should be noted that this volume is not a new edition of volume I, but is an up-to-date work dealing with materials

not dealt with in that volume. It cannot be too highly praised; it is very well written and produced, and is a book that will appeal equally to producers and users of irons and steels containing nickel.—J. FERDINAND KAYSER.

KÖHLER, E. L. "*Englisch–deutsches und deutsch–englisches Wörterbuch für die Eisen- und Stahl-Industrie.*" Sma. 8vo, pp. xii + 168 + 162. Vienna, 1955: Springer-Verlag. (Price 47*s.* 6*d.*)

This dictionary should be found extremely useful by English readers and translators of German technical literature; it should prove, moreover, of equal service to German readers. The fact that American spelling, and a large number of American expressions, has been used will not greatly inconvenience either section.

The main emphasis of the book is on the practical side of iron- and steel-making and of heavy engineering, but metallography has not been neglected; the whole work reflects the author's long and considerable experience of metallurgy at Österreichisch-Alpine Montangesellschaft at Leoben-Donawitz.

The standard of production of the volume is high, the print is clear, and the stout binding should allow it to stand up to frequent use.—J. P. S.

LESSELLS, JOHN M. "*Strength and Resistance of Metals.*" 8vo, pp. xiv + 450. Illustrated. New York, 1954: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd. (Price 80*s.*)

This is primarily a textbook for engineers, dealing with the behaviour of metals, especially steel, under various kinds of stressing. Nevertheless, the book is of considerable interest to metallurgists, because it shows the sort of information that engineers require and how they use this information.

The scope is considerable, covering, for example, tensile behaviour at room and elevated temperatures, hardness, impact, fatigue, fracture, strain hysteresis, mechanical wear, theories of strength and working stresses. The text is well planned and subtitled, and in many chapters there is a specific section giving the significance of the subject to the engineer. The information is sound and very clearly expressed. Throughout the book there is a quiet but distinct air of authoritative knowledge. One cannot turn far in this book without finding some aspect of stress knowledge correlated with practical design. Much of the treatment is descriptive but using simple formulæ in mechanics, although reference is also made to advanced theory. A useful collection of problems is appended.—A. R. BAILEY.

MILTON, R. F., and W. A. WATERS (Editors). "*Methods of Quantitative Micro-Analysis.*" Second edition. 8vo, pp. xi + 742. Illustrated. London, 1955: Edward Arnold (Publishers), Ltd. (Price 70*s.*)

This invaluable text-book covers practically the entire field of micro-analysis, the principal exception being spectrography. In keeping with recent practice, it is the work of several contributors skilfully incorporated by the editors into a coherent and comprehensive whole.

The text is divided into eight principal parts. The first covers general techniques, with special reference to gravimetric methods. Part II deals in detail with the analysis of organic compounds. Part III is devoted to volumetric analysis and Part IV to colorimetric methods including absorptiometry, nephelometry and fluorimetry. In Part V are described the various electrochemical methods, including potentiometry, polarography, deposition, and conductimetry. Techniques involving the measurement of gas are contained in Part VI; the examples quoted range from conventional gas analysis to the determination of the oxygen uptake of sewage in the presence of activated sludge, and of carbon monoxide in blood. These six Parts comprised the first edition, from which they have been virtually reprinted with very few modifications or additions; consequently, references to developments since 1948 are lacking. Parts VII and VIII, dealing with chromatographic and biological methods, respectively, were not included in the earlier edition. In the former are quoted typical examples of inorganic analysis by partition and ion exchange methods. The latter is devoted to the assay of vitamins.

The various authors discuss, often at length, the sources of error which may arise during the course of analyses, and indicate methods for minimizing their effects. But when, as so often happens, heterogeneous material is being tested, correct inferences can be drawn only from analyses of representative samples, and nowhere has the primary importance of good sampling been mentioned.

Despite its inevitable minor shortcomings, this second edition should prove a worthy successor to the first, especially in those laboratories where chromatographic and biological methods are employed.—M. P. MENDOZA.

NEW PUBLICATIONS

AMERICAN IRON AND STEEL INSTITUTE. "*The Saugus Iron-works Restoration.*" An Industrial Landmark Restored. A revised and up-to-date version on "The First Iron Works Restoration" published in 1953. 8vo, pp. 31. Illustrated. New York, 1955: The Institute. (Price 25 cents)

AMERICAN SOCIETY FOR TESTING MATERIALS. "*ASTM Specifications for Carbon- and Alloy-Steel Plates for Boilers and Pressure Vessels (Excluding Corrosion-Resisting Steel Plates).*" 8vo, pp. 90. Illustrated. Philadelphia, Pa., 1954: The Society. (Price $1.75)

BRITISH IRON AND STEEL FEDERATION. "*Annual Report* 1954." La. 4to, pp. 50. Illustrated. London [1955]: The Federation.

BRITISH IRON AND STEEL RESEARCH ASSOCIATION. "*Conference on Works Transport.*" (Plant Engineering Division and Operational Research Section.) Held at Ashorne Hill, Leamington Spa, July 6th and 7th, 1954. La. 4to, pp. 44. Illustrated. London, 1954: The Association. (Price 5*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 153: Part 3A: 1954. "*Girder Bridges.*" Part 3. "*Loads and Stresses.*" Section A. "*Loads.*" 8vo, pp. 47. Illustrated. London, 1954: The Institution. (Price 6*s.*)

BRITISH STANDARDS INSTITUTION. B.S. 1121: Part 33: 1955. "*Methods for the Analysis of Iron and Steel.*" Part 33. "*Iron in Ores, Slags and Refractories.*" 8vo, pp. 10. London, 1955: The Institution. (Price 2*s.* 6*d.*)

BRITISH STANDARDS INSTITUTION. B.S. 2561: 1955. "*Forged Steel Pipe Fittings. Screwed with API Thread for the Petroleum Industry.*" 4to, pp. 12. Illustrated. London, 1955: The Institution. (Price 3*s.* 6*d.*)

BRITISH STANDARDS INSTITUTION. B.S. 2569: Parts 1 and 2: 1955. "*Sprayed Metal Coatings.*" Part 1. "*Protection of Iron and Steel against Atmospheric Corrosion.*" Part 2. "*Protection of Iron and Steel by Aluminium against Corrosion at Temperatures between 120° C. and 950° C.*" 8vo, pp. 7 each. London, 1955: The Institution. (Price 2*s.* each)

BRITISH STANDARDS INSTITUTION. "*British Standards Yearbook*, 1955." 8vo, pp. [iii +] 435. London, 1955: The Institution. (Price 12*s.* 6*d.*)

CLARK, GEORGE L. "*Applied X-Rays.*" Fourth edition. (International Series in Pure and Applied Physics.) 8vo, pp. ix + 843. Illustrated. New York, Toronto, London, 1955: McGraw-Hill Book Co., Inc. (Price 89*s.* 6*d.*)

ECONOMIC COMMISSION FOR EUROPE, STEEL COMMITTEE. "*Recent Advances in Steel Technology and Market Development*, 1954." La. 4to, pp. xii + 55. Illustrated. Geneva, 1955: United Nations. (Price 3*s.* 9*d.*, or 2 fr. Swiss or $0.50)

INGENIÖRSVETENSKAPSAKADEMIEN and CHALMERS TEKNISKA HÖGSKOLA. "*Proceedings of the International Symposium on the Reactivity of Solids, Gothenburg*, 1952." Two volumes. La. 8vo; Part I, pp. xxx + 1–592; Part II, pp. 593–1102. Illustrated. Gothenburg, 1954: The Societies. (Price (two Parts) 65 Sw. Kr.)

"*The Instrument Directory and Buyers' Guide.*" An Auxiliary to "*Instrument Practice.*" La. 4to, pp. 208. London, 1955: United Trade Press. (Free to subscribers to "*Instrument Practice.*")

IRON AND STEEL BOARD. "*Development of the Iron and Steel Industry, 1953 to 1958.*" Presented to Parliament in pursuance of Section 16 (2) of the Iron and Steel Act, 1953. 8vo, pp. iv + 42. Illustrated. London, 1955: H.M. Stationery Office. (Price 1*s.* 9*d.*)

D. L. BLEWETT, J.P.

DANIEL LESLIE BLEWETT, the son of a steelworker, was born at Gowerton, Glamorgan, in 1897, and was educated at Gowerton Grammar School.

On leaving school in 1912, Mr. Blewett became a junior chemist in the Gowerton Steelworks of the West Wales Section of Richard Thomas and Baldwins, Limited. He showed an aptitude for administration at an early age, and in 1936 he became Works Manager of the Gowerton Steelworks. His next appointment was as Area Steel Works Manager of the West Wales Section; in this post he was responsible for eight Works. In 1954 he took up his present appointment as Assistant General Manager of the Section, thus adding to his responsibilities several sheet works and two tinplate works.

Mr. Blewett has always been interested in progressive education and training policy, especially in regard to his own Company, where he is Chairman of the Board of Governors of the Apprentices' Training School and of the Joint Advisory Apprentice Committee. He is also a Governor of the Gorseinon College for Further Education and a member of the West Glamorgan Divisional Education Committee, and since 1949 he has been a Justice of the Peace for Glamorgan.

A member of the South Wales Siemens Association, Mr. Blewett has been a member of the South Wales Sub-Committee of the British Iron and Steel Research Association for over nine years. After many years of service on the Council of the Swansea Metallurgical Society, he was elected to serve as its President for the Session 1953–54.

D. L. Blewett, J.P.

Honorary Member of Council, 1953–54